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REFERENCE

Lane, B. H., 1935, Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C. 35c.)

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American Journal of Science

MARCH 1954

THE EFFECTS OF ROTATIONAL ROLLING ON THE FABRIC AND DRYING SHRINKAGE OF CLAY

W. O. WILLIAMSON

ABSTRACT. Cylinders made by rolling a kaolinite-illite clay were artificial R-tectonites with lineations parallel to the axis of rotation. Such cylinders became tubes as deformation proceeded. This phenomenon resembled the manufacture of metal tubes by the Mannesmann process. The ease with which it occurred may have depended on the greater water contents of the interiors of the cylinders. Fabrication of a cylinder by rolling involved flow of the clay flakes both along and around the axis. Flow around the axis produced a helicitic structure associated with a direction of rotation opposite to that deducible from the occurrence of the same structure in a porphyroblast. The reason for the apparent anomaly is given. The connection between differential drying shrinkage and the orientation of clay flakes is illustrated by the progressive change in these two characteristics which accompanied deformation.

INTRODUCTION

The fabric of solid cylinders made by rolling clay to and fro has been cursorily described. Thus Williamson (1947a) noted its similarity to that obtained by extruding clay through a circular orifice, while Weymouth and Williamson (1953a) found it compatible with the fabric of the tectonites produced, according to Knopf and Ingerson (1938), by deformation processes which resembled the rotational rolling of dough on a board. It was not mentioned that tubes, as well as cylinders, can be formed by the rolling of clay.

The present account describes the micro-structures developed by rolling clay in one direction and their relationship to the accompanying megascopic features, water distributions, and drying shrinkages.

MATERIALS AND METHODS

The clay was an English kaolinitic "blue ball clay" which contained 20-30 percent of illite. Other significant constituents were fine-grained quartz and minute authigenic prisms of rutile and tourmaline. There were 74.9 percent by weight of particles less than one micron in equivalent spherical diameter (Weymouth and Williamson, 1953a, 1953b). Microscopical preparations were made from the shaped specimens in the manner already described. The only modification was the mounting of some of the pyroxylin-backed clay films in thermoplastic resins instead of in Canada balsam. The disposition of (001) surfaces was found by optical examination; such surfaces were those on which the basal pinacoids of the clay-mineral crystals lay within the oriented aggregates produced by sedimentation or by flow (Wey-

mouth and Williamson, 1953a). The directions of lineations, which were observable microscopically by noting the arrangement of prisms of rutile and tourmaline, and of certain oriented clay aggregates elongated in the (001) surfaces, were checked in the following manner. The clay film, of which the disposition relative to its parent specimen had been recorded, was examined microscopically in circumstances such that this disposition was not apparent to the observer. The presumed direction of lineation was noted and only afterwards was its orientation within the specimen established. This method, although unmentioned, was used in earlier studies (Williamson, 1941, 1947b; Weymouth and Williamson, 1953a).

Two types of specimen were subjected to deformation: (1) Clay spheres with no consistent orientation of (001) except at their surfaces; (2) Clay cylinders in which (001) was perpendicular to their axes.

The specimens were deformed on a stationary glass plate by rolling them discontinuously in one direction by pressure from a second parallel glass plate held in the hand. Both plates were wider than the maximum lengths of the deformed specimens. Practice allowed the preparation of a cylinder which had been deformed symmetrically on the sides of a plane that bisected its axis perpendicularly and contained the direction of rotation.

Water contents and shrinkages were found by drying specimens at 105°C.; they were calculated on the weights and lengths respectively of the wet clay.

The megascopic features of comparably deformed plasticene specimens were examined also but, unless the contrary is stated, all phenomena recorded later were those shown by the "ball clay."

THE DEFORMATION OF CLAY SPHERES

The Clay Spheres

These were made from clay which had been "aged" in the plastic state for some months. The clay was rolled into balls which weighed ca. 10 gm. each and were ca. 2.1 cm in diameter; because its water content approached that required to cause stickiness the clay was readily deformable. Typical water contents appear in tables 1 and 2.

TABLE 1

Effect of progressive deformation, indicated by the diameter of the specimen, on differential drying shrinkage of cylinders in which (001) was originally perpendicular to the length (or axis). No. 1 was not deformed. Diameters and associated shrinkages measured on those parts of the cylinder where the clay diaphragm between the terminal cavities was in existence longest. No. 5 was a tube.

No. of Specimen	1	2	3	4	5
Mean diameter of specimen (cm)	2.00	1.96	1.73	1.67	1.65
d, mean percentage linear shrinkage along diameter	9.05	8.91	8.76	12.19	10.20
l, mean percentage linear shrinkage along length	19.09	11.91	10.33	7.74	9.79
Ratio d/l	0.47	0.75	0.84	1.57	1.04
Percentage water content of specimen	32.86	31.32	30.69	32.27	30.26

TABLE 2

Effect of progressive deformation, indicated by the diameter of the specimen, on the differential drying shrinkage of cylinders made from spheres. Diameters, etc., measured as in table 1. No. 7 was nearly pierced, while no. 8 was a tube.

No. of Specimen	1	2	3	4	5	6	7	8
Mean diameter of specimen (cm)	2.05	1.95	1.92	1.77	1.67	1.63	1.61	1.46
d, mean percentage linear shrinkage along diameter	11.37	13.08	13.88	12.62	11.55	11.95	8.71	9.46
l, mean percentage linear shrinkage along length	10.05	12.48	9.50	9.61	8.15	7.95	8.12	8.24
Ratio d/l	1.13	1.05	1.46	1.31	1.42	1.50	1.07	1.15
Percentage water content of specimen	29.44	29.88	29.83	29.68	29.36	29.54	28.94	n.d.

Megascopic Effects of Deformation

Rolling first produced a cylinder of which the rounded ends were relics of the curved surface of the former sphere; the length of the cylinder was now slightly greater than the diameter of this sphere. The rounded ends became flatter as the outer layers of the cylinder flowed parallel to its axis. This preferential movement of the outer over the inner layers caused bell-mouthed terminal cavities to develop, sometimes before the ends of the cylinder were completely flat. The bases of these cavities became linked by a canal, and the cylinder was transformed into a tube (fig. 1). Rolling of this tube, even

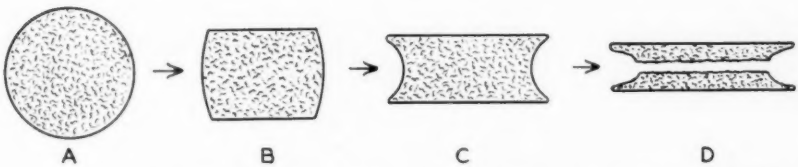


Fig. 1. Rotational rolling of a clay sphere A produces successively a cylinder B, a cylinder with hollow ends C, and a tube D. Diagrammatic sections following an equatorial plane of the sphere and planes of symmetry containing the axes of the remaining solids. See also plate 1, figure 3.

under very light pressure, readily produced a hollow triangular prism. The same changes in form appeared when a clay sphere was rolled to and fro instead of one way, but a triangular prism easily developed even before the terminal cavities became continuous. In general, with either type of rolling, it was difficult to avoid obtaining a tube; this tube appeared despite considerable variations in water content or pressure. The most successful method of making a cylinder with a long solid section between the terminal cavities was to and fro rolling under relatively strong pressure; this was used to prepare the "rolled rods" employed in certain earlier studies (Williamson, 1947a; Weymouth and Williamson, 1953a).

The Use of Markers

Markers are insets of colored clay, or incised lines, which help to reveal the flow pattern in a strained specimen.

On the curved surface of a cylinder—At stage B of figure 1 a straight strip of colored clay was let into the curved surface from end to end and parallel to the axis. Further deformation caused the strip to stretch along its length and, at its ends, to move forward slightly in the direction of rolling. The projections so formed occurred where pressure on the specimen was particularly effective. When terminal cavities appeared, the strip bent back sharply over them to make acute angles with the direction of rolling. This was because pressure was less effectively applied to the hollow, more deformable, parts of the cylinder and the clay tended to lag behind (fig. 2).

Small circular pieces of dyed clay were inserted into the curved surface, again at stage B of figure 1. Rolling caused the circles to become ellipses which had their major diameters parallel to the axis of the cylinder except near the ends where these diameters were at acute angles to the direction of rolling; thus the major diameters were aligned with the distorted colored strip just described (fig. 2).

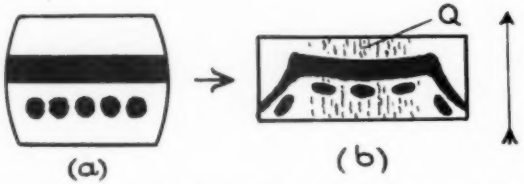


Fig. 2. Diagrammatic sketch of the curved surface of a clay cylinder showing the effects of subsequent rolling on the disposition of strip-like and circular markers. Sutures caused by tension (Q-joints) marked Q in (b). Long arrow indicates direction of rolling. See also plate 1, figures 1 and 2.

Lines of equal depth were scratched on the curved surface of the cylinder, except in the vicinity of the ends, both parallel and perpendicular to the axis. On further rolling, the lines parallel to the axis were eliminated before those perpendicular thereto; the latter widened because of the axial tension which accompanied the lengthening of the cylinder. Weymouth and Williamson (1953a) have already noted that lines, or more commonly sutures, approximately at right angles to the axis appeared spontaneously on cylinders that were rolled to and fro. These surface markings depended on the irregular failure in tension of the outer layers and were cognate with the *ac* cracks which, according to Knopf and Ingerson (1938, p. 151) were found in rocks that had suffered comparable natural deformation. The surface markings did not, however, develop readily during the steady deformation caused by the uni-directional rolling of the present experiments (fig. 2).

Within the specimen.—A clay sphere was cut in half and the halves cemented together by a flat film of dyed clay. Rolling of the repaired sphere

was about an axis within this film which became identical with the axis of the developing cylinder. When the cylinder had reached stage B or C of figure 1 it was dried and dissected. The originally flat film was now S-shaped because the outer had moved over the inner layers of the cylinder in the direction of rolling. The curvature of the S-shape was more pronounced away from the ends of the specimen, i.e., where the original thickness had been greatest and the shortening perpendicular to the axis was thus at a maximum. The S-shape resembled the helicitic arrangement of inclusions in a rotated porphyroblast in a metamorphic rock. In such a porphyroblast an S-shape indicates anticlockwise and an Ƨ-shape clockwise rotation (Turner, 1948, p. 151; Mügge, 1930, fig. 20; pl. 29, figs. 19 and 20). This is because the core of the porphyroblast, which is the oldest part, has rotated more than the outer layers. The core of the present specimen has rotated less than the outer layers; thus an S-shape indicates clockwise and an Ƨ-shape anticlockwise rotation (fig. 3).

Fig. 3. Diagrammatic section at right angles to the axis of a rolled clay cylinder showing helicitic structure formed by distortion of an originally planar film of colored clay. Small projections, just below the surface, point in the direction of rotation. They depend on the retardation of flow caused by friction at this surface. See also plate 1, figure 4.

The S-shapes produced in the laboratory were often modified near the ends of their limbs by small pointed projections in the direction of rotation. These appeared because the friction at the contacts with the glass caused the most rapid movement to occur not at, but just beneath, the surface of the clay (fig. 3). The projections were more pronounced away from the ends of the cylinders; the reason was similar to that already given for the more pronounced curvature of the S-shape in the same region.

At the ends of a cylinder.—The ends of a cylinder were inscribed with radial lines before or after the formation of cavities (stages B and C, fig. 1). The lines became slightly curved as rolling proceeded. This curvature was sympathetic with that of the S-shapes described above and was similarly produced by the movement of the outer over the inner layers in the direction of rolling. As the cavities deepened, the incised radii broadened at their bases, i.e., near the points of emergence of the axis of the cylinder. This effect implied a stretching of the clay surface which accompanied the formation of the bell-mouths of the cavities (fig. 4).

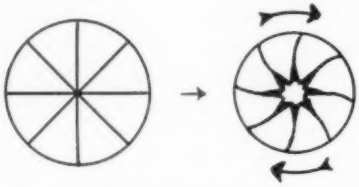


Fig. 4. A clay cylinder is changed to a tube by rolling. Diagrammatic sketch of the effects on radii incised on the end of the original cylinder. The radii become curved and also broaden near the mouth of the canal in the tube.

The completely pierced cylinder (stage D, fig. 1) had bell-mouthed cavities at the ends, joined by a tubular canal. Along this canal the surface of the clay was broken by numerous ribs which were approximately parallel to the axis of the cylinder. These ribs resulted from the outcropping of shear joints. Similar joints were visible at the ends of the cylinder on the convex surfaces at stage B, or, more particularly, in the bell-mouthed cavities of stages C or D (fig. 1). They bent inwards from the curved surface of the cylinder in the same sense as the distorted incised radii mentioned already. Shear joints in the bell-mouthed cavities and in the canal were presumably cognate but their forms in space were not necessarily identical; the behavior of the markers described above (fig. 2) suggested that deformation in the two regions had followed somewhat different courses.

CHANGES IN MICRO-STRUCTURE DURING THE DEFORMATION OF CLAY SPHERES

In an undeformed sphere (001) tended to be parallel to the surface in a zone of limited depth, but throughout most of the sphere bore no fixed relationship to this surface (fig. 5a). The arrangement of (001) was not,

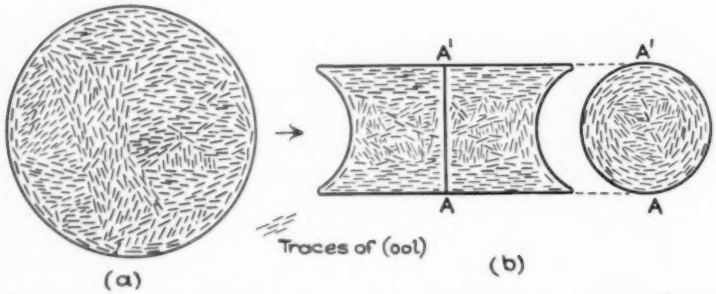


Fig. 5. Diagrammatic sections showing the traces of (001).

(a) In an equatorial plane of a clay sphere: the traces are parallel to the curved surface in a zone of limited depth beneath which, although not systematically arranged, they are often mutually parallel.

(b) In planes of symmetry parallel and perpendicular to the axis of the cylinder formed by rolling the above sphere; planar parallelism to the curved surface extends inwards to a central region in which (001) has not yet been markedly reoriented.

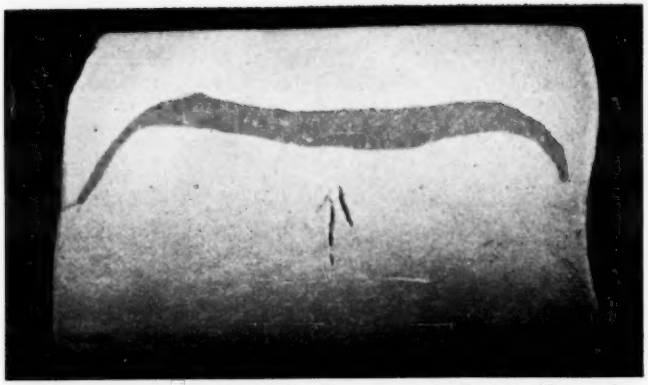


Fig. 1. Effect of continued rolling on originally strip-like markers (compare text fig. 2). X 3. The ends of the colored strip project contrary to the direction of rolling.

Fig. 3. Same specimen as in figure 1 showing that it is actually a tube. X 3.

Fig. 2. As in figure 1 but pressure applied more strongly toward the righthand end. X 3. Direction of rolling as in figure 1.

PLATE 1

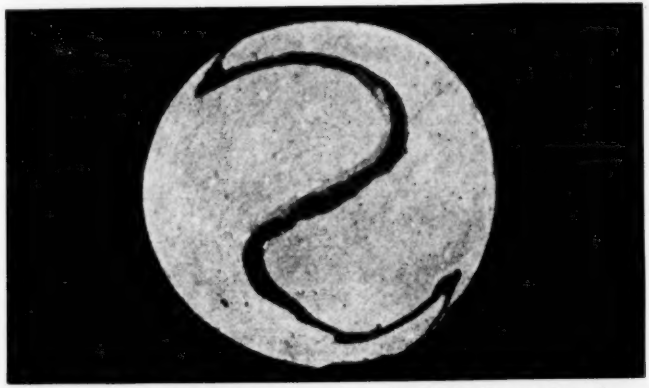


Fig. 4. Artificial helicitic tsructure. Anticlockwise rotation (compare text fig. 3). X 3.

however, completely random, for oriented aggregates had been formed by plastic flow when the clay was manipulated prior to and during the fashioning of the sphere. During rolling (001) became reoriented parallel to the curved surface of the lengthening cylinder. This reorientation began in the outer layers and, because these flowed axially to provide the clay which surrounded the terminal cavities, it was also obvious here (fig. 5b). When the cylinder had become a tube the reorientation was virtually complete. That reorientation caused (001) to become parallel to the curved surface of the cylinder was indicated not only by the optical methods described by Weymouth and Williamson (1953a) but by X-ray diffraction technique.

The well-developed systems of shear joints identified microscopically by Weymouth and Williamson (1953a) in extruded cylinders of clay were not apparent. This was because the progressive reduction in the diameters of the rolled cylinders caused any shear joints which developed to become rapidly inoperative as their angles with the curved surface changed; their courses were then obscured during the flow of the adjacent clay. Sections from planes of symmetry containing the axis of the cylinder showed, however, narrow ill-defined strips in which the orientation of the clay-mineral crystals differed somewhat from that in the matrix; these strips made various angles, rarely greater than 35°, with the traces of the curved surface. They appeared to be relics of those shear joints which had been most recently active. Their possible arrangement in space is discussed later.

In sections at right angles to the axis of the cylinder shear joints were not apparent unless these sections cut the terminal bell-mouthed cavities. Such annular sections were traversed by traces of the curving shear joints visible megascopically (see above). These shear joints were, as usual, filled by clay in which the orientation of (001) differed from that in the matrix. If traces of similar shear joints existed in parallel sections further from the ends of the cylinder, their curvature must have approached more nearly that of the (001) surfaces of the matrix. This could render them indistinguishable by optical methods (Weymouth and Williamson, 1953a).

Micro-preparations of reoriented clay from the curved surface of a cylinder, or from deeper layers parallel to this surface, revealed an obvious lineation. This was marked by the arrangement of prisms of rutile and tourmaline and by the disposition of the major diameters of oriented clay aggregates of the type described by Weymouth and Williamson (1953a) as occurring in comparable sections of extruded cylinders. The lineation followed the length of the cylinder, except at the ends where it bent back in the manner of the strip-like marker shown in figure 2.

THE WATER DISTRIBUTION IN SPHERES AND CYLINDERS

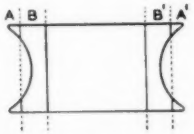
Williamson (1947a; 1947b) showed that the deformation of certain clay-containing specimens caused systematic variations in the distribution of water therein; these variations were not reduced by storing the specimens

for some days in saturated air. The same phenomena were detected in the present study.

Layers 3-4 mm thick, peeled from the exteriors of five clay spheres, had water contents of 29.13-30.36 percent which were 0.39-1.00 less than those of the corresponding interior portions with 30.13-30.75 percent. Two of the spheres, stored for a week in saturated air, had differences in water content between the exteriors and interiors which were not less than those shown by two of the remaining three specimens which had been stored for only 20 minutes, ¾ hour, and 2½ hours respectively; these latter times approximated to those which elapsed between the fabrication of spheres and the subsequent deformation by rolling in the experiments described earlier.

Cylinders were dissected at stages B or C of figure 1 by removing the curved surface to a depth of 3-4 mm either immediately after their fabrication or after they had been stored for 15 days in saturated air. In five replicates the outer layers had water contents of 28.32-29.23 percent which were 0.43-1.58 less than those of the more interior portions of the specimens with 29.27-29.90 percent. One of the two stored specimens showed a difference greater than those of two of the three unstored specimens.

Other cylinders, at stage C of figure 1, had annuli ca. 3-4 mm wide cut from the lips of the terminal cavities. In six replicates (i.e., three specimens) the annuli AA′ had water contents of 28.02-29.73 percent which were 0.40-1.26 less than those of the neighboring segments marked BB′ in figure 6 with 29.28-30.18 percent. These dissections were of freshly prepared specimens.



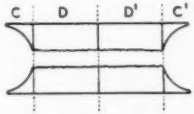


Fig. 6. Diagrammatic section along the axis of clay cylinder with terminal cavities showing adjacent segments A and B, A′ and B′ of which the water contents were found.

Fig. 7. Diagrammatic section along the axis of a clay tube showing adjacent segments C and D, C′ and D′, of which the water contents were found.

Finally, cylinders were rolled until they became tubes and were immediately dissected according to the scheme shown in figure 7. In six replicates (i.e., three specimens) the end sections CC′ had water contents of 28.02-28.91 percent which were 0.09-0.70 lower than those of the respective adjoining sections DD′ with 28.72-29.31 percent.

The lower water contents of the annuli or end sections cut according to figures 6 or 7 developed because these sections contained material from the outer, i.e., less hydrous, layers of the cylinder. The adjoining sections had substantial proportions of material from the more hydrous interior.

In all the dissections the lower water contents appeared where reorientation had caused the clay flakes to achieve a high degree of mutual parallelism, i.e., in the outer layers of the spheres and cylinders and in the clay surrounding the terminal cavities of the latter. Williamson (1947a; 1947b) showed that, in certain deformed clay or clay-rich specimens, the least hydrous regions were those where parallel orientation was best developed. However, the rolling of the present specimens could aggravate the less hydrous character of their outer layers by causing a loss of water to the glass surfaces in contact; indeed, water derived from the clay was detectable on these surfaces.

The interior of a cylinder, because of its greater water content, could yield under stresses smaller than those required to cause flow in the drier outer layers. This may explain the ease with which tubes developed from solid cylinders. Support was given to this hypothesis by the behavior of plasticene. Cylinders of plasticene failed to yield tubes at room temperature but tubes were readily obtained from the heated material. Admittedly, the hot plasticene was much more deformable, but it is possible that deformation could occur most readily in the interiors of the cylinders; not only might these regions be richer in liquid but they would be the warmest parts of the specimens. It must, however, be noticed that the production of tubes by rolling plastic clay or plasticene resembles the manufacture of tubes from hot metal rods by the Mannesmann process, although here the metal flows over tools within the tubes (Alexander and Street, 1951, fig. 27; Doan and Mahla, 1941, fig. 216). Even in this process there is the possibility that the interior is the more deformable part of the rod because it may be warmer than the outside, while in addition the latter may be work-hardened by the rolls.

THE DEFORMATION OF CLAY CYLINDERS OF SPECIFIC FABRIC

The specimens were sets of cast circular discs, 2 cm in diameter, luted together by moistening the broad faces. In the resulting cylinder (001) was dominantly at right angles to the axis. Similar cylinders had been used to fill the reservoir of the extruder in the experiments of Weymouth and Williamson (1953a). As in these experiments some cylinders contained discs dyed with methylene blue arranged alternately with unstained discs.

Rolling caused changes in shape of the type already described. The cylinder lengthened, while cavities appeared in its ends; in these cavities were the outcrops of curved shear joints. Finally the cavities became connected by a canal and the former cylinder was now a tube. Shear joints outcropping on the inner surface of this tube appeared as ridges following the length of the canal.

The principal change in micro-structure was the reorientation of (001) from perpendicular to parallel to the axis. This change extended progressively inwards from the curved surface and accompanied the flow along the length of the cylinder which caused the terminal cavities to be walled by reoriented clay (fig. 8). In the final tubular specimen the reorientation was most pro-

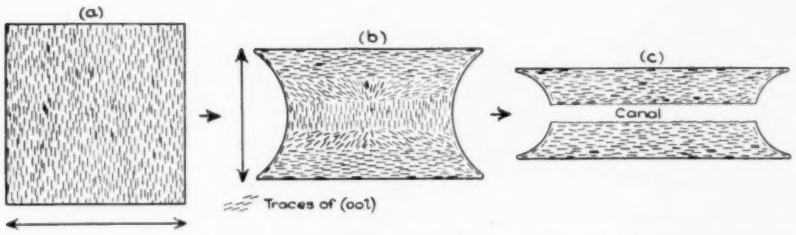


Fig. 8. Clay cylinder (a) with (001) perpendicular to the axis. Rolling changes it to cylinder (b). Here reorientation of (001) parallel to the curved surface has occurred in a deep zone extending inwards to a central region where the original disposition of (001) is maintained. Long arrows indicate the directions of maximum drying shrinkage in (a) and (b).

Further rolling produces a tube (c). Outwards from the canal of this tube are seen successively a narrow zone with (001) parallel to the walls of the canal, a zone of poorer orientation and finally a broad zone in which (001) is parallel to the external curved surface.

Diagrammatic sections coinciding with planes of symmetry containing the axes of the cylinders or tube.

nounced in a deep zone beneath the external curved surface; it was pronounced also in a very shallow zone around the tube which joined the cavities. Between the two zones was a narrow third zone in which reorientation was less perfect.

Reoriented clay at the curved surface of the cylinder, or in planes beneath and parallel to this surface, showed lineations of the type found in cylinders made by the deformation of spheres (see above), i.e., linear elements were noticeably parallel to the axis except near the ends of the cylinder where they bent in a sense opposite to the direction of rotation.

Shear joints were, for reasons stated earlier, not well developed in the deformed cylinders; the micro-preparations, however, showed traces of shear joints which were more obvious than those found in cylinders which had evolved from spheres. In sections which represented planes of symmetry containing the axis of the cylinder these traces were in two directions, making angles rarely greater than 35° with the traces of the curved surface. In sections perpendicular to the axis the traces of the shear joints crossed the general fabric in which (001) was disposed parallel to the curved surface of the cylinder. Presumably the traces of shear joints in the two types of section were related to the shear joints seen in the canal and to the curving shear joints in the terminal cavities. It is possible, however, that the joints in the cavities were arranged differently in space from those encountered in sections far from the ends of the cylinder for, as explained earlier, the deformation histories of the two localities are not identical.

In an extruded cylinder the shear joints followed the curved surfaces of two sets of cones or "semi-ellipsoids," both symmetrical about the axis; the apices of each set pointed in a direction opposite to that of the other (Weymouth and Williamson, 1953a). If a rolled cylinder were formed merely

by contraction perpendicular to the axis accompanied by the flow of clay parallel thereto, a very similar disposition of shear joints could be postulated (Van Iterson, 1947, fig. 128). However, because differential rotation of clay about the axis is involved also, the arrangement of joints in space must be more complex. This arrangement could not be confidently diagnosed because the traces of the joints were not well seen in the micro-sections.

The deformation of cylinders, made from discs of stained and unstained clay alternately arranged, suggested that the ideal flow pattern, as seen in planes of symmetry containing the axis of the cylinder, was that of figure 9b.

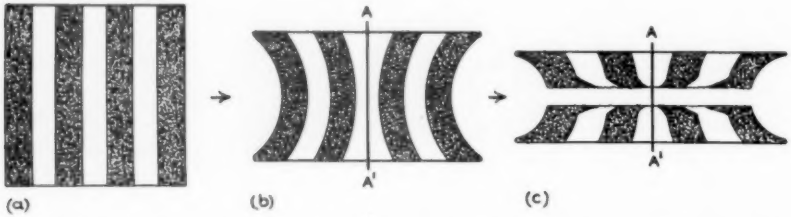


Fig. 9. Diagrammatic sections coinciding with planes of symmetry containing the axes of the cylinders or tube (compare fig. 8). The cylinder (a) is made of discs; alternate discs are dyed. Rolling produces the cylinder (b) and the tube (c) and deformation is symmetrical about the plane of which the trace is AA'.

It is not claimed that the curves representing the deformed discs are mathematically correct. Further, in actual specimens, the velocity gradient between the outside and the interior, which accompanies plastic flow, may be steeper than suggested in the figure; also, maximum velocity is not at but below the surface because of frictional drag.

Microscopical study showed that the boundaries between the color bands remained parallel to the (001) surfaces in their vicinity throughout deformation where flow alone was involved. The boundaries were occasionally displaced by joints in a manner which indicated that these had been correctly diagnosed as "shear joints"; Weymouth and Williamson photographed a better example of the same phenomenon (1953a, pl. 2, fig. 1). In such circumstances local boundaries between dyed and undyed clay need not be parallel to (001).

Figure 9b ignores the development of the canal which ultimately links the terminal cavities; the appearance of this canal resulted in a disposition of the color bands like that of figure 9c. Both figures ignore minor distortions of the color bands near the outer curved surface produced not so much by friction in the manner mentioned in the next paragraph as by the fact that the original cylinder had slight ridges caused by the somewhat rounded edges of the constituent discs. In the early stages of deformation the flattening of these ridges promoted a particularly strong local orientation of (001) parallel to the curved surface; Weymouth and Williamson (1953a) described a similar phenomenon in the unextruded residue of their experiments.

Ideally, sections at right angles to the axis of the deformed cylinder should show circles or annuli of dyed and undyed clay. In reality there were irregularities both in the construction of the original specimen and in the subsequent deformation process. Thus in some of the sections the dyed and undyed clay appeared as areas of crescentic and related form. Where these areas approached the trace of the curved surface they were subject to minor distortions, caused by friction, related to the projections just beneath the clay surface shown in figure 3.

THE EFFECT OF DEFORMATION ON DIFFERENTIAL DRYING SHRINKAGE

Cylinders of specific fabric.—Williamson (1947b) showed that in a clay indistinguishable from the one here studied the drying shrinkage perpendicular to (001) surfaces was greater than that parallel thereto, irrespective of whether the mutual parallelism of these surfaces had been caused by sedimentation or by plastic flow. This has been confirmed.

A cast disc of the type used in constructing a cylinder of specific fabric has a drying shrinkage at right angles to the broad faces, i.e. at right angles to (001), which is greater than that parallel thereto (Williamson, 1947b). Thus a cylinder made of such discs in parallel arrangement shrank much more along its axis than along its diameter (specimen no. 1, table 1). Rolling caused (001) to change progressively in orientation from perpendicular to parallel to the axis, and thus increased the drying shrinkage perpendicular to the axis at the expense of that parallel thereto (fig. 8). Finally the drying shrinkage perpendicular to the axis became the greater of the two (table 1, specimen no. 4). This arrangement persisted in the tubular specimen no. 5, but the relative magnitude of the shrinkage perpendicular to the axis decreased because the specimen was hollow.

Cylinders derived from spheres.—Table 2 shows that the drying shrinkage perpendicular to the axis tended to increase relatively to that along the axis as the cylinder was rolled, i.e. as (001) was progressively reoriented parallel to this axis. The sudden decrease in the ratio of the shrinkages in specimens no. 7 and 8 depended on the fact that no. 7 was nearly and no. 8 completely pierced by the canal which forms in the later stages of deformation. The change in the shrinkage ratio with increasing deformation is less regular than in table 1. This is unlikely to depend essentially on unavoidable experimental error. The undeformed specimens, unlike those of table 1, did not have (001) arranged in a known preferred orientation. On the contrary, they were spheres in which the disposition of (001), except at the surface, was irregular. It was not, however, random because the fabrication of the sphere involved plastic flow which could cause the formation of extensive regions in which (001) tended to common parallelism (see above). If such a region had (001) disposed so as to allow the fabric of the resulting cylinder to develop with little rearrangement of the clay flakes, then this fabric, and the associated differential drying shrinkage, would resemble those appropriate to a stage in deformation beyond that suggested by the megascopic features

of the cylinder, e.g., by the length of its diameter quoted in tables 1 and 2 as a measure of the degree of deformation. A similar argument can be developed to show that, in other instances, the fabric and shrinkage behavior could seem appropriate to an earlier stage of deformation than was indicated by the megascopic features.

PETROFABRIC ANALOGIES

A cylinder formed by rolling was an artificial R-tectonite produced by a rotational process more severe in its effects than that which any comparable natural tectonite has experienced. In such a cylinder movement of the outer over the inner layers occurred both around and along the axis, but the movement along the axis was probably the more important. If, however, the axis be called *b*, the plane of symmetry at right angles to it contains *ac* (fig. 9). Certain surface markings represent Q-joints parallel to this plane, and caused by tension along *b* (fig. 2). Except near the ends of the cylinder, where the course of deformation was peculiar, the obvious lineation followed *b*.

SUMMARY

(1) The rotational rolling of spheres of fine-grained kaolinite-illite clay produced cylinders which developed terminal cavities and finally became tubes.

(2) The formation of tubes may have been assisted by the lowered resistance to stress which accompanied the greater water contents found in the interiors of the cylinders.

(3) Rolling caused the basal pinacoids of the clay-mineral crystals to become parallel to the axis of the developing cylinder; thus was produced a drying shrinkage greater along the diameter than along the axis. The relative magnitude of the shrinkage along the diameter increased with increasing reorientation of the clay flakes.

(4) The rearrangement of the basal pinacoids accompanied movement of the outer over the inner layers of the cylinder not only along but around the axis.

(5) The latter movement was made obvious by developing artificial helicitic structures.

(6) A rolled cylinder was an artificial R-tectonite; microscopical features and the behavior of markers of dyed clay revealed a prominent lineation parallel to the axis.

(7) Near the ends of the cylinder this lineation bent in directions opposite to that of the rotary motion. Thus the history of deformation in these vicinities differed from that elsewhere in the cylinder.

(8) Shear joints were produced during rolling but were too poorly developed for their arrangement in space to be completely elucidated; a reason for their poor development is suggested.

(9) The rolling of cylinders made of discs of dyed and undyed clay alternately arranged showed that the surfaces along which the color bands were in contact remained parallel to those in which the basal pinacoids of the clay flakes were arranged in the immediate vicinity, provided that flow only was involved. Movement along shear joints caused local lack of parallelism between the two sets of surfaces.

ACKNOWLEDGMENTS

I am indebted to Dr. G. F. Walker for interpreting the X-ray diffraction patterns yielded by certain specimens and to Mrs. E. B. Knopf for helpful criticism of the manuscript.

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AGE OF THE KATAHDIN GRANITE*

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ABSTRACT. The contact of the Katahdin granite with Silurian strata is exposed opposite the new power house just below Ripogenus Dam, Piscataquis County, Maine. The granite is intrusive into the Silurian strata but has had very little effect upon them. It is probable that the granite is of post-Early Devonian age because its relatively fresh condition indicates that it was emplaced subsequent to the Acadian orogeny, which in this area folded beds as young as late Early Devonian.

INTRODUCTION

The age of the numerous bodies of granitic rock exposed in the northern Appalachians is a major problem in the geology of that region. Only in a few places have the contacts between these granitic bodies and the adjacent stratified rocks been observed. In still fewer places have fossils been found in the stratified rocks adjacent to these contacts. It is the purpose of this note to describe the nature of the contact between the Katahdin granite and the strata it intrudes, as observed on the West Branch of the Penobscot River below Ripogenus Dam (fig. 1, loc. 2) in central Maine.

The Katahdin granite[1] below Ripogenus Dam is probably of post middle Silurian age as shown by its intrusive relationships with beds underlying those that contain middle Silurian fossils. It possibly postdates the regional deformation, as indicated by the unaltered appearance of the granite and the presence near the contact of veinlets containing fresh stilbite crystals. The youngest deformed strata in the region are of Early Devonian age.

Formal names for seemingly new stratigraphic units are not here proposed because field work has not been sufficient to establish the validity and lateral relationships of these units.

STRATIGRAPHIC RELATIONSHIPS NEAR THE CONTACT OF THE KATAHDIN GRANITE

It is pertinent first to consider the stratigraphy of the adjacent stratified rocks. A well-exposed section of these strata is present in the vicinity of Ripogenus Dam (fig. 1, loc. 1).

The oldest stratum, exposed on the west side of Ripogenus Dam, is basalt. Fisher (in Willard, 1945, p. 67), suggested that the term "Ripogenus volcanics" be applied to the basalt, but the name Ripogenus is preoccupied by Toppan's Ripogenous [Ripogenus] series (Toppan, 1932, p. 71). Basalt of similar appearance is present in that portion of Piscataquis County bordering Ripogenus Lake and extending to the southwest in the direction of Kokadjo. The top of the basalt is well exposed in the gorge of the Penobscot River below the dam, but the base has not been observed. The total thickness, therefore, cannot be determined. Examination of exposures and of drill cores taken from the vicinity of a new power development in Ripogenus Gorge shows that the basalt is at least a few hundred feet thick. It consists of several separate flows, most of them less than a few tens of feet thick where studied in the vicinity of Ripogenus Dam. To the northwest on Chesuncook Lake (fig. 1,

* Publication authorized by the Director, U. S. Geological Survey.

[1] Katahdin granite of Toppan (1932, p. 69).

loc. 3) coarse agglomerates and boulder breccia are present, and their lithologic similarity to the basalt at Ripogenus Dam suggests that they are correlative with it.

Overlying the basalt below Ripogenus Dam is a discontinuous band of specular hematite that is about half an inch thick. This layer of hematite may be a dehydrated and much compressed remnant of limonitic weathering products derived from the underlying basalt prior to the deposition of the overlying conglomerate.

The specular hematite is overlain by predominantly arenaceous beds, which consist of about 10 to 15 feet of a basal, dark-colored conglomerate that grades up into about 20 to 30 feet of buff to greenish-gray, coarse- to medium-grained, massive quartzitic sandstone. Most of the pebbles in the conglomerate consist of white and hematite-stained vein quartz, have an average diameter of about an inch, and are moderately well rounded. The argillaceous material surrounding the pebbles is hematiferous, as indicated by its red streak. No fossils have been recovered from the conglomerate or the quartzitic sandstone. The age of the hematite, as well as that of the underlying basalt, is thought to be either early or middle Silurian because it is no more deformed than the overlying Chesuncook limestone of Fisher (in Willard, 1945, p. 67), which contains a fauna of middle Silurian (Niagaran) age. The contact of the quartzitic sandstone with the overlying limestone (Willard, 1945, p. 67) is characterized by several feet of relief. The basal portion of the limestone contains sand grains similar to those in the underlying quartzitic sandstone.

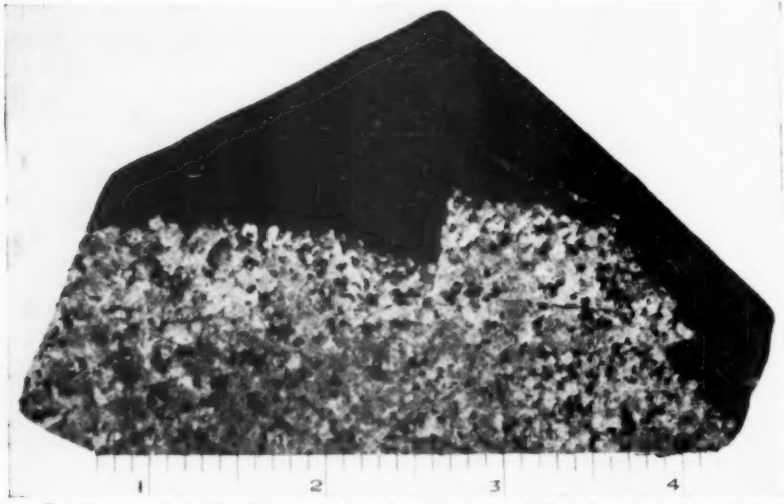
The relationships of some of the rock units on Chesuncook Lake suggest that relative degree of deformation may be a valid criterion for discriminating between strata laid down before and those laid down after the Taconic revolution in this area. At location 5 (fig. 1), on the southeast shore of Chesuncook Lake, highly deformed, olive-drab, phyllitic slate (possibly of Cambrian and Ordovician age) interbedded with much-fractured gray quartzite appears to underlie less-deformed, fossiliferous beds that are lithologically similar to Fisher's Chesuncook limestone. The actual contact has not been observed at location 5 (fig. 1), as the shore in that locality is covered by glacial debris. It is notable that the basalt and probably the quartzitic sandstone, both of which are present at Ripogenus Dam, are not present beneath the fossiliferous limestone at location 5. This hiatus is inferred to be due to an unconformity, of at least local significance, at the base of Fisher's Chesuncook limestone that possibly cut out the quartzitic sandstone and the basalt. Alternate explanations are that the units involved are highly variable in thickness or that the junction is a fault rather than a sedimentary contact.

CONTACT OF THE KATAHDIN GRANITE

The contact of the Katahdin granite with the above-described sedimentary units is about a quarter of a mile downstream from the dam, in the vicinity of the new powerhouse. Just to the south of the powerhouse, on the west side of the Penobscot River, the granite cuts across the basalt (pl. 1). Xenoliths of basalt up to 8 feet in diameter are present in the granite adjacent to the

PLATE 1

A. Contact of Katahdin granite and quartzitic sandstone (note the narrow band of discolored quartzite).



B. Contact of the Katahdin granite and basalt that underlies the quartzitic sandstone. Scales show inches and tenths of inches.

contact. Granite also intrudes the basalt to the north, in the tunnel that carries water from the dam to the powerhouse (oral communication, Irving Crosby, 1952). On the east bank of the river, opposite the powerhouse, layers of

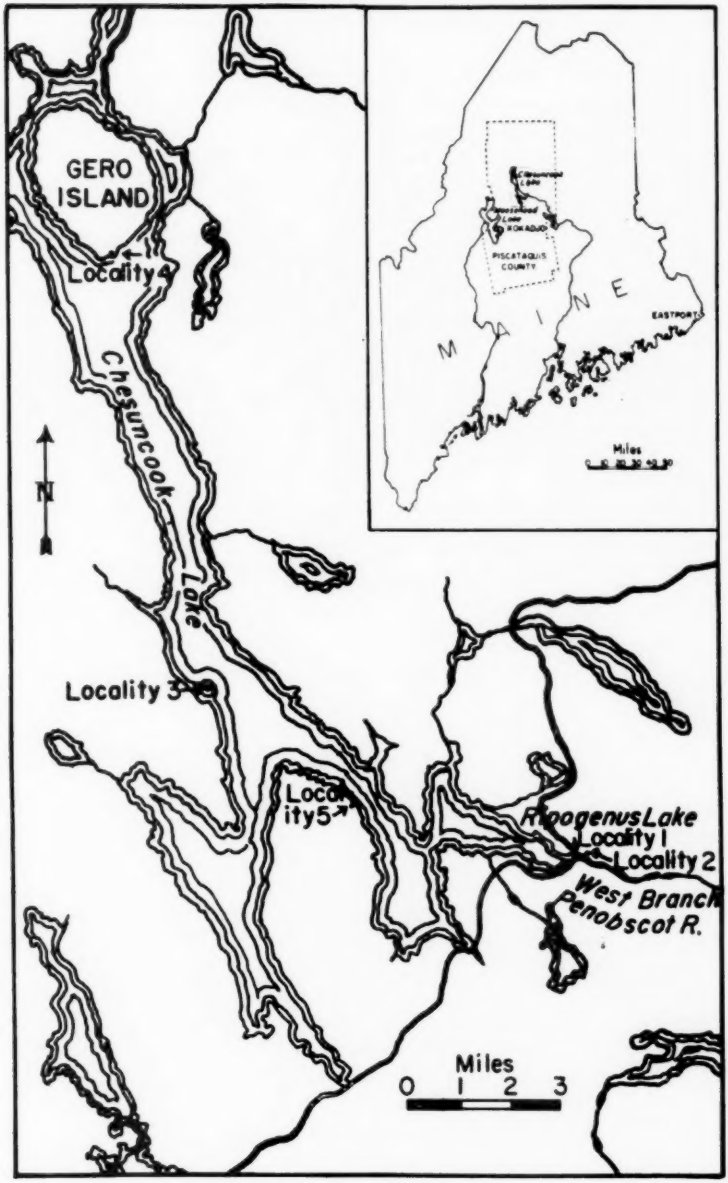


Fig. 1. Chesuncook-Ripogenus Lake area, Piscataquis County, Maine.

granite up to a foot thick are in lit-par-lit relationship with the quartzitic sandstone. The granite has not altered the intruded strata at this locality, with the exception of a discolored rim a few inches wide (thin sections of this rim contain shreds of biotite not present in the adjacent sandstone). Some of the joints in the sandstone near the contact are coated with 1-mm crystals of stilbite. These layers of granite may be traced to the south directly into the main body of granite that abruptly cuts off the quartzitic sandstone strata and the basalt. Elsewhere in the vicinity irregular-shaped bodies of granite crosscut the quartzitic sandstone.

According to Toppan (1932, p. 72), "the Katahdin granite is intrusive into this series [his Ripogenous series] as it cuts the quartzites about midway of the Ripogenous Gorge." At the locality to which he refers (loc. 2 on fig. 1) the granite cuts the quartzitic sandstone (his "coarse grit") rather than "the quartzites" (which he reports as overlying what Fisher later (1941) called the Chesuncook limestone). Toppan undoubtedly observed the relationships of his Katahdin granite and the quartzitic sandstone at this locality but his report is not clear on this point.

The contact of Fisher's Chesuncook limestone and the granite is not exposed at this locality. It seems likely that the relationship between the limestone and the granite is intrusive, i.e., like that between the granite and the strata that underlie the limestone.

To the north of Ripogenus Lake on the southern end of Gero Island (loc. 4, fig. 1) in Chesuncook Lake is exposed a gray slate, similar in its lithology to the Seboomook slate (of Perkins, 1925, p. 375). This slate is reported by Perkins to be of Silurian age. The slate on Gero Island, however, has yielded a fauna of Oriskany age that includes the following fossils: *Platyceras* sp., *Beachia thunii*, *Follmanella mainensis*, *Leptocoelia flabellites*, pelmatozoan columnals, an unidentified orthoceracone, an unidentified encrusting bryozoan, *Meristella* sp., *Isorthis?* n. sp., *Dalmanites*, or *Odontochile* (identification by A. R. Palmer). This slate is deformed to no less a degree than the strata of Silurian age in this part of Piscataquis County. It seems likely, therefore, that both the Silurian and the Lower Devonian strata in this part of northern Maine were deformed simultaneously. The unaltered condition of the Katahdin granite seems to preclude the possibility that the granite had been intruded into the strata exposed on the West Branch prior to the deformation that affected the adjacent strata of Lower Devonian age, and that it was possibly intruded subsequent to the folding that affected both the Silurian and the Lower Devonian strata of this region. The time of this folding is thought to be Middle Devonian, although no direct evidence is available in Piscataquis County. The nearest area in which Acadian folding has been demonstrated is the vicinity of Eastport, Maine (Bastin and Williams, 1914).

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DEPTH HABITATS OF SOME SPECIES OF PELAGIC FORAMINIFERA AS INDICATED BY OXYGEN ISOTOPE RATIOS

CESARE EMILIANI

ABSTRACT. Different species of pelagic Foraminifera have been found to occupy different habitats with respect to temperature and water density, and therefore, indirectly, also with respect to depth. The same species may vary considerably its depth habitat in order to adjust itself to the proper temperature and water density.

The relative positions of the different specific populations with respect to these factors are the same in the areas here considered, that is, in the Gulf of Mexico, the equatorial Atlantic, and the eastern equatorial Pacific. No pelagic population was found to live at a depth greater than about 220 m.

The species *Orbulina universa* occupies progressively shallower depth habitats during its growth, while the other species here examined maintain their depth habitats during at least most of their lives.

Small variations with time in the relative positions of different specific populations of pelagic Foraminifera have occurred during the Pleistocene in the eastern equatorial Pacific. The cause of these changes is probably genetic.

The temperature of the ocean water in an area of the eastern equatorial Pacific and its variations during the Pleistocene and in portions of the Tertiary were recently determined by analyzing the oxygen isotopic ratios in the calcium carbonate of pelagic and benthonic Foraminifera from deep-sea cores (Emiliani, 1954).

This study showed that different species of pelagic Foraminifera from the same core levels registered different temperatures, from which it was concluded that they lived at different depths. This fact was confirmed when material from other areas was analyzed. General similarities and trends between all samples were recognized, although significant variations in time or

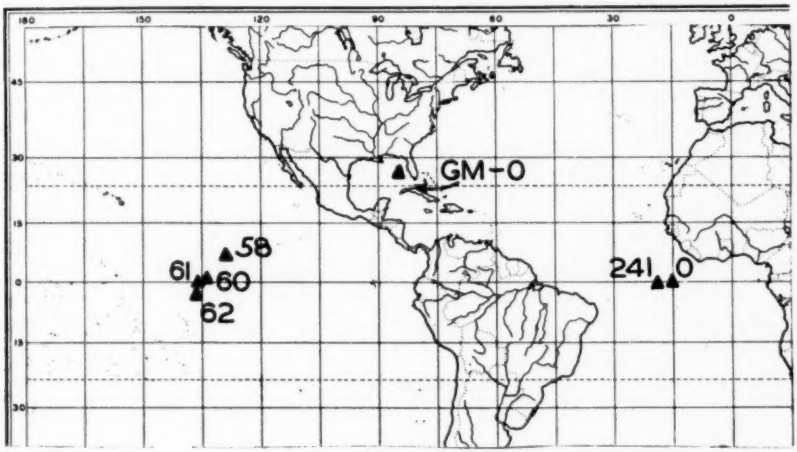

Fig. 1. Geographic location of the samples.

TABLE 1
Locations of the Samples and Water Data

Sample	Area	Geographic Coordinates		Ocean Temperature (°C.)				$\delta_{O^{18}}$ of Sea Water at Surface
		Lat.	Long.	Surface February	Surface August	200 m	400 m	
GM-O	Gulf of Mexico	26°00′N	84°41′W	22	29	15	10	+0.77
O	Equat. Atlantic	0°1′S	15°16′W	27	23	13	9	+0.48
241	" "	1°10′N	19°50′W	27	23	13	9	+0.48
58B	Equat. Pacific	6°44′N	129°28′W	26	26	13	10	+0.22
58	" "	6°44′N	129°28′W	26	26	13	10	+0.22
60	" "	1°35′N	134°57′W	24	24	13	10	+0.22
61	" "	0°06′S	135°58′W	24	24	13	10	+0.22
62	" "	3°00′S	136°26′W	25	25	13	10	+0.22

space may occur. Figure 1 and table 1 show the locations of the samples together with the temperature of the ocean waters at the surface and at 200 and 400 meters of depth. The O^{18} composition of superficial waters, based on figures published by Epstein and Mayeda (1953), are also given. None of these data was available for the exact locations of the samples here studied, but some were available within short distances. All O^{18} data of the waters are relative to mean ocean water.

From the O^{18} analyses of the foraminiferal shells and the waters it is possible to obtain the exact temperatures at which the Foraminifera lived. In the analyses of Foraminifera, a comparatively large number of tests of the same species (from 100 to 400 or more, depending upon the weight of the individual tests) were selected, so as to make up the minimum of 4-5 milligrams of $CaCO_3$ needed for each spectrometrical analysis. The results represent, therefore, the mean temperature at which the specimens cumulatively examined grew. These results are shown in the temperature column of table 2, and all have an error of $\pm$ 0.5°C., corresponding to about $\pm$ 3 standard deviations.

The majority of the species here examined appear to grow at essentially the same temperatures in the three different areas. However, *Globorotalia tumida* shows some variations, registering a temperature of 18.9° C. in the Gulf of Mexico, 16.5°C. in the equatorial Atlantic, and 15.2°C. in the eastern equatorial Pacific. Also, *Pulleniatina obliquiloculata* shows a temperature around 22°C. in the Gulf of Mexico and in the equatorial Atlantic, while it registers a temperature of 18.6°C. in the eastern equatorial Pacific.

In general, there appears to be a well-defined stratification with respect to temperature, with *Globoratalia truncatulinoides* preferring the coldest environment and *Globigerinoides conglobata, rubra* and *sacculifera* preferring the warmest.

The variations of temperature with depth for the three areas here considered (figs. 2, 3 and 4) are based on data from Schott (1926, 1935) and on data kindly furnished by Dr. R. N. Ginsburg of the University of Miami.

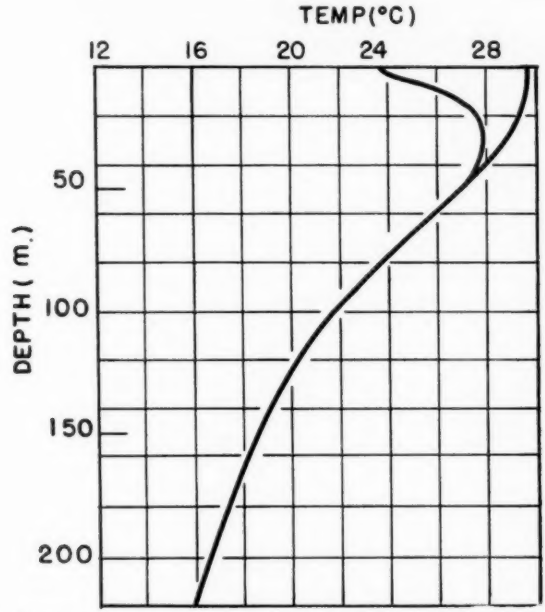

Fig. 2. Variation of temperature with depth in the eastern Gulf of Mexico.

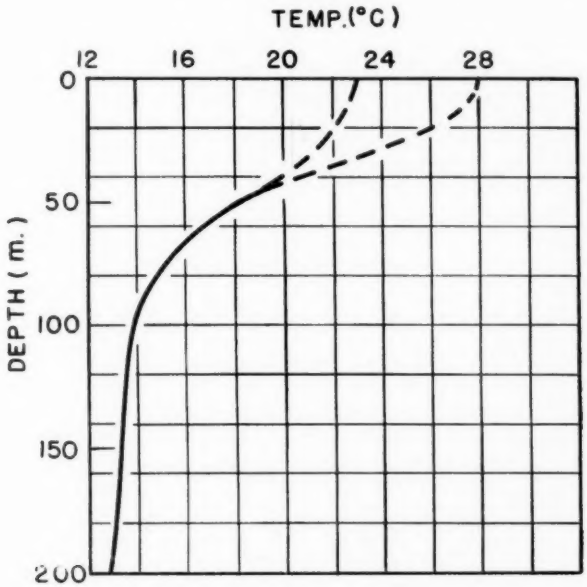

Fig. 3. Variation of temperature with depth in the equatorial Atlantic.

TABLE 2

Temperature and Depth Habitats of Pelagic Foraminifera

Species	Sample	Temp. (°C.)	Depth habitat (m)
Globigerina dubia	GM-O	21.9	100
" "	O	20.5	35 – 38
" "	241	20.6	33 – 38
Globigerinoides conglobata	GM-O	23.2	80
" rubra	GM-O	27.2	0 – 45
" sacculifera	GM-O	25.1	0 – 10
" "	O	25.1	0 – 25
" "	241	25.6	0 – 25
Globorotalia menardii	GM-O	19.8	130
" "	O	19.4	43
" "	241	19.2	43
" truncatulinoides	GM-O	16.1	220
" tumida	GM-O	18.9	140
" "	O	16.8	55
" "	241	16.2	62
" "	58B	15.2	130
Orbulina universa	GM-O	19.8	130
Pulleniatina obliquiloculata	GM-O	21.6	100
" "	O	22.4	15 – 35
" "	241	21.3	30 – 35
" "	58B	18.6	110

With these data available it is possible to calculate the depths at which the different species live. It should be observed that the depth values thus obtained and shown in the last column of table 2 merely indicate the depth at which the maximum density of a given foraminiferal population occurred. The actual vertical dispersion could be determined only by separately analyzing for temperatures a certain number of individual tests of Foraminifera, which is obviously impossible because of their far insufficient weights.

The species *Globigerinoides conglobata*, *rubra* and *sacculifera* appear to occupy the shallower habitats, followed by *Globigerina dubia*, *Pulleniatina obliquiloculata*, and *Globorotalia menardii*, while *Globoratalia tumida* and *truncatulinoides* occupy the deeper habitats. This order is generally observed in the three localities.

The stratification with respect to temperature is, therefore, reproduced also with respect to depth; however, as already well known, the different species appear to be much less dependent upon pressure than upon temperature. *Globorotalia tumida*, for instance, appears to live at a depth of 140 m in the Gulf of Mexico, while it lives around 55 m in the equatorial Atlantic. The difference in pressure is around 8.5 atmospheres.

The densities of sea water and their variations with depth (table 3) have been calculated from data available in Schott (1926, 1935) and from data submitted by Dr. R. N. Ginsburg, using the tables given by Ennis (1944).

From these density data (table 3) and the depth data (table 2) it is possible to deduce the densities of the sea waters in which the different species live. The results (table 4) show that the same species appear to be adapted to waters of the same densities in the different areas, even if this involves considerable differences in pressure.

TABLE 3

Temperatures, Salinities and Densities of Ocean Waters

	Temp. (°C.)	Sal. ‰	Density
Gulf of Mexico			
surface	22-29	35.7	1.022-1.024
50 m	26.5	36.5	1.024
100 m	21.5	36.5	1.026
150 m	18.5	36.0	1.027
200 m	16.5	36.0	1.027
Equatorial Atlantic			
surface	25.5	34.6	1.023
50 m	18.0	35.5	1.026
100 m	13.8	35.4	1.027
150 m	13.2	35.3	1.027
Eastern Equatorial Pacific			
surface	28.0	34.2	1.022
50 m	28.0	34.4	1.022
100 m	20.5	34.7	1.025
150 m	13.0	34.5	1.027

The capacity of a certain foraminifer to live in a water of a certain density depends, obviously, upon its specific weight; this, in turn, depends upon (a) the specific weight of the protoplasm and its inclusions, (b) the specific weight of the test, and (c) the ratio of the mass of the protoplasm and

TABLE 4

Sea Water Densities at which Different Pelagic Species Live

	Gulf of Mexico	Equatorial Atlantic	East Equatorial Pacific
Globigerina dubia	1.026	1.026	—
Globigerinoides conglobata	1.025	—	—
" rubra	1.022-1.024	—	—
" sacculifera	1.022-1.024	1.023-1.024	—
Globorotalia menardii	1.026	1.026	—
" truncatulinoides	1.027	—	—
" tumida	1.027	1.026	1.027
Orbulina universa	1.026	—	—
Pulleniatina obliquiloculata	1.026	1.025	1.025

inclusions to the mass of the test. If the first two factors are assumed to be roughly constant for all species, the important factor appears to be the third

one, i.e. the ratio of the mass of the protoplasm and inclusions to the mass of the test. For a given locality, species in which this ratio is the largest will prefer shallower habitats, while species with a smaller ratio will occupy deeper habitats. From table 4, it appears that species like *Globigerinoides conglobata, rubra* and *sacculifera* are the lightest, while *Globorotalia tumida* and *truncatulinoides* are the heaviest. If specific weight surpasses a certain limit, which depends upon the density of the water, the foraminifer may not be able to live within a reasonable distance from the surface and may find itself in a zone too deep for efficient nutrition. This has probably been a factor of fundamental importance for the origin and evolution of pelagic Foraminifera. Mutations of pelagic species toward a decrease of the ratio mass of protoplasm to mass of test are most probably deadly, as are mutations of benthonic species in the opposite direction. Theoretically, a pelagic foraminifer could modify its water density habitat by changing the amount of inclusions in the protoplasm or the ratio of the mass of protoplasm and its inclusions to the mass of the test. Such changes, however, seem rather unimportant, the different specific populations showing, as will be seen later, a remarkable rigidity to relative vertical displacements.

A foraminiferal species will change its depth habitat during its lifetime if growth processes modify the ratio above mentioned. To test this hypothesis, samples of *Globigerina dubia, Gl. inflata, Globigerinoides conglobata, Gl. sacculifera, Globorotalia menardii, Gl. truncatulinoides, Gl. tumida, Orbulina universa, Pulleniatina obliquiloculata,* and *Spaeroidinella dehiscens,* from different parts of the world, were each divided into two size-groups, a larger one between 1.00 and 0.50 mm, and a smaller one between 0.50 and 0.25 mm. Only the samples of *Orbulina universa* showed an appreciable temperature difference between the two size-groups, the larger size-groups yielding a temperature 1.5-3°C. higher than the smaller one. Since these samples are from a Pleistocene core from the Mediterranean (core no. 189 of the Swedish Deep-Sea Expedition (1947-1948), it is difficult to estimate what depth interval is represented by the obtained temperature differences. This has actually little importance, because different values would have been obtained if different size-groups had been selected. The important thing is that younger individuals of *Orbulina universa* occupy different depth habitats than older ones. This is readily explained by the fact that in this species, while the mass of protoplasm increases proportionally to the cube of the diameter of the test, the mass of the test increases proportionally to only the square of the diameter, the thickness of the wall remaining approximately constant. Therefore the animal grows progressively lighter and progressively migrates toward the surface.

Absence of temperature differences between the two size-groups of all other species here considered indicates that the ratio mass of protoplasm and inclusions to mass of the test remained in all cases constant during the period of time involved. This does not include the very early ontogenetic stages, for which it has not been possible to make adequate tests. Apart from the free-swimming gamonts, which have probably a comparatively large depth

range, individuals of all species in very early neanic stages probably occupy somewhat different depth habitats than in later stages.

The numerous analyses of Foraminifera from eastern equatorial Pacific cores showed that the distribution of the different specific populations through time, with respect to temperature, is remarkably constant. Four of these cores, nos. 58, 60, 61, and 62, are of interest here. Core 58 has a length of 991 cm and includes the last $2.5 \cdot 10^6$ years (Arrhenius, 1952), reaching well into the Pliocene. Core 60 has a length of 1013 cm covering the last 750,000 years and including most of the Pleistocene. Core 61 has a length of 1029 cm reaching back 500,000 years and covering about half of the Pleistocene. Finally, core 62 has a length of 1479 cm covering $1.5 \cdot 10^6$ years and reaching somewhat into the Pliocene.

Globorotalia tumida is present in all the samples available from these cores and is usually very abundant. This species has been taken as a basis of reference, and the differences d_t between the temperature registered by a given species and the temperature registered by *Globorotalia tumida* have been calculated. These differences represent how distant on the thermic scale were the zones of maximum densities of the populations considered. To this, depth distances evidently correspond, but, since the graph shown in figure 4

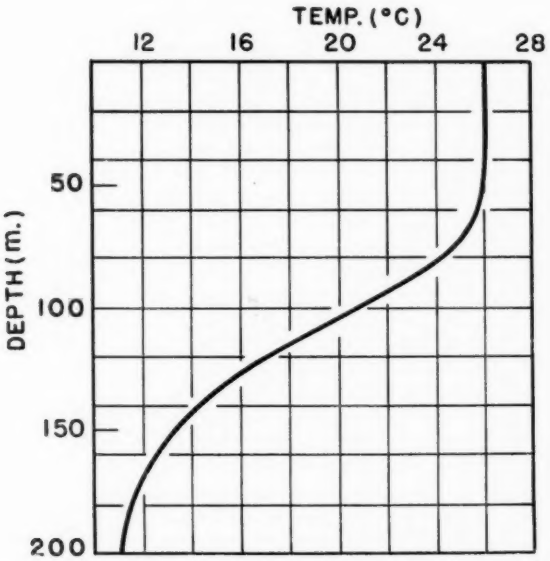

Fig. 4. Variation of temperature with depth in the eastern equatorial Pacific.

is available only for the present time and it is difficult to estimate its shape in the past, it is equally difficult to estimate what these depth distances actually were.

The number of d_t values available from each core is shown in the column f of table 5. If only one value was available, it is shown in the column M. If two or three values were available, column M shows their arithmetic mean. If four or more d_t values were available, their mean, the standard error of the mean σ_M, the standard deviation σ and its standard error σ_σ were calculated.

TABLE 5

Statistics of d_t Values for Different Pelagic Species from Eastern Equatorial Pacific Cores

	Sample	f	d_t (°C.) M	σ_M	σ	σ_σ
Globigerina dubia	58	4	3.3	0.4	0.7	0.3
" "	60	10	3.1	0.2	0.8	0.2
" "	61	1	2.3	—	—	—
" rotundata	58	3	2.0	—	—	—
" "	61	5	2.8	0.1	0.2	0.1
Globorotalia menardii	58	1	3.8	—	—	—
" "	60	8	3.0	0.3	0.8	0.2
" "	61	2	4.0	—	—	—
Pulleniatina obliquiloculata	58	12	3.5	0.1	0.5	0.1
" "	60	13	3.9	0.2	0.6	0.1
" "	61	7	4.0	0.1	0.3	0.1
Sphaeroidinella dehiscens	58	6	3.3	0.3	0.7	0.2
" "	62	1	2.0	—	—	—

Taking 6σ as a limit, it appears that the d_t values did not vary more than 4.8°C. in any case. Also, it seems that the variations of the d_t values were larger for *Globigerina dubia* and *Globorotalia menardii* and smaller for *Pulleniatina obliquiloculata* and *Globigerinoides rotundata*. If the assumption is made that the graph of figure 4 roughly obtains, the variation of 4.8°C. may be estimated to correspond to a relative vertical displacement of about 30 meters of the zones of maximum population densities.

It is interesting to see whether the variations of the d_t values are related to time, that is, whether the relative distances between the zones of maximum density of two specific populations have changed in a certain direction with time. For this purpose, the correlation coefficients between core stratigraphic levels and the d_t values of *Pulleniatina obliquiloculata* have been calculated for core 58 and core 60, where respectively 12 and 13 d_t values were available (table 6). It is evident that, while in the shorter (relative to time) core 60 there is no correlation, in the longer core 58 there appears to be a definite correlation ($P<0.01$). This correlation, incidentally, is negative, that is, the d_t values were generally smaller in the earlier times. Therefore, the density maxima of the two populations of *Pulleniatina obliquiloculata* and *Globorotalia tumida* were closer toward the end of the Pliocene and moved apart with time. This displacement, although significant, was certainly small. In fact, the d_t value of *Pulleniatina obliquiloculata* in the most recent sample of core

58 is 4.4°C. which, if the graph in figure 4 obtains, may be estimated to correspond to a vertical distance of about 30 m. On the other hand, the d_t

TABLE 6

Correlation Factors and Probability Levels between d_t Values for *Pulleniatina obliquiloculata* — *Globorotalia tumida* and Temperature and Depth in Cores 58 and 60

Correlation between	Core No.	N	r	P
d_t and depth	60	13	+0.41	~0.20
d_t and temperature	60	13	−0.44	~0.15
d_t and depth	58	12	−0.73	<0.01
d_t and temperature	58	12	−0.39	~0.20

value of the earliest available sample in the same core is 2.5°C., which would correspond to a vertical distance of about 20 m. Therefore, the maximum relative displacement of the two maxima of population density was only of about 10 meters.

With the available data, it is difficult to estimate which one of the two specific populations moved or whether both did. If more data were available, this problem could be solved by relative comparisons of a certain number of different specific populations.

Correlation coefficients have also been calculated between the d_t values of *Pulleniatina obliquiloculata* from cores 58 and 60 and the temperatures registered by *Globorotalia tumida* (table 6). In this case there appears to be no correlation at all in either of the two cores, as may be seen from the comparatively high values of the probability level P. Lack of correlation means that the vertical displacements discussed above were not induced by temperature changes but were due to other environmental factors or to genetic factors related to populations equilibria.

The absence of correlation between the d_t values and temperature is rather surprising. Since Foraminifera are more sensitive to temperature than pressure, as discussed above, and since climatic changes would probably affect first the superficial waters and then penetrate slowly downwards, shallower populations should be the first to react and to seek adjustment by means of some vertical displacements. This does not seem to be the case here. Either the population of *Pulleniatina obliquiloculata* or *Globorotalia tumida*, or both, seem to have moved vertically in a certain direction over a long period of time, quite independently of thermic changes. The comparatively small values of these changes may have had something to do with this, in the sense that bigger changes would probably have had a significant effect. Vertical displacement could also have been brought about by differential variations in the density of the sea water, but it is difficult to see how this could have happened, particularly in a regular way and over a long period of time. Perhaps the best explanation is offered by genetic factors.

CONCLUSIONS

The zones of maximum densities of populations of pelagic Foraminifera are stratified in a definite order with respect to temperature and water density, and therefore also, indirectly, with respect to depth. Different populations of the same species show small tolerance toward variations of temperature and water density, and may occupy considerably different depths in different regions, in order to adjust themselves to the more important temperature and water density factors.

In the material so far examined, no evidence has been found of populations living at depths greater than about 220 meters.

All species examined, except *Orbulina universa*, maintain unchanged their depth habitats during at least most of their lives. On the other hand, *Orbulina universa* occupies progressively shallower depth habitats while growing.

Finally, the considerable reluctance of foraminiferal populations to vertical displacements, in a given area, and the independence of these displacements from at least small temperature variations, enhance the possibility of using pelagic Foraminifera from cores for paleoclimatologial studies.

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MINERALOGICAL AND SIZE ANALYSIS OF WEATHERING ZONES ON ILLINOIAN TILL IN INDIANA

CONRAD P. GRAVENOR

ABSTRACT. Three Illinoian till sections from Indiana were sampled at one-foot intervals from the surface down to the fresh till. Mechanical analysis shows a gradual decrease in size of material from the unleached till to the top of the gumbotil zone. It is believed that this reduction in size is due mainly to the disintegration of the larger fragments by soil solutions moving along mineral grain boundaries. Two sections from western Indiana show a layer of weathered loess on top of the gumbotil. Heavy mineral analyses indicate that apatite is unstable and amphiboles and pyroxenes are moderately stable under the conditions of weathering which produced the gumbotil. Examination of the clay fraction in the weathered and unweathered till shows that illite is the dominant clay mineral and kaolinite and montmorillonite are present in minor amounts.

INTRODUCTION

Weathering of Illinoian till in Indiana has produced a mature soil profile in which the till is largely decomposed in the upper zones. Leighton and MacClintock (1930) have divided similar Illinoian till profiles into five zones:

1. Surficial soil—humus zone, may be partly loess
2. Highly weathered zone containing resistant pebbles
3. Leached zone
4. Oxidized but unleached zone
5. Unaltered drift

The purpose of the present study is to determine the degree of decomposition of the heavy and clay minerals throughout the weathered profile and to define the origin of the surficial soil.

Three Illinoian till sections from the sides of strip-mining pits in Indiana were sampled: the first from Brazil, the second from a location 18 miles east of Terre Haute on Highway 45, and the third from North Vernon. These sections are referred to as "A," "B," and "C" respectively. At each location the tills were sampled at one-foot intervals starting 6 inches below the surface and continuing downward to unleached parent material. These samples are numbered consecutively from the surface down to the base of each section. Each sample was analyzed for size distribution and the result plotted on a triangular diagram. Heavy minerals and clay minerals were separated from each sample of profile "B" and identified.

MECHANICAL ANALYSIS

Each sample was split into three components: sand and gravel, silt, and clay according to the size classification of the United States Bureau of Soils. The amount of clay present in each sample was recorded by means of a soil hydrometer. The results of these analyses are shown in figures 1, 2, and 3.

Profile "A" (fig. 1).—Samples 1 to 4, which were taken from the top 4.5 feet, show less than 10 percent sand and no gravel, about 60 percent silt, and between 25 and 35 percent clay. Below 4.5 feet there is a gradual increase in the amount of sand and gravel, a diminishing amount of silt, and a slight decrease in clay.

Profile "B" (fig. 2).—Profile "B" is similar to "A" with the exception that the silt zone extends to a depth of 6.5 feet below the surface.

Profile "C" (fig. 3).—There is no noticeable size break in profile "C." Both sand and gravel are found in the surface samples and increase in amount

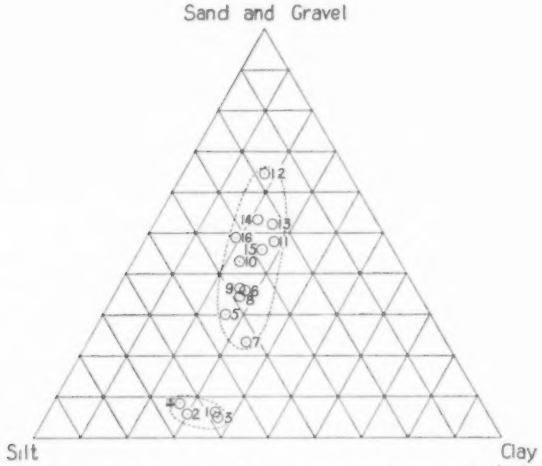


Figure 1. Mechanical analyses of samples from profile "A"

downward through the section. The parent till at the base of the profile is less stony than that of profiles "A" and "B."

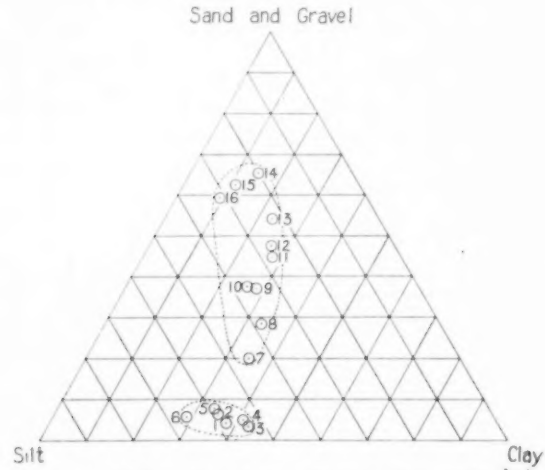


Figure 2. Mechanical analyses of samples from profile "B"

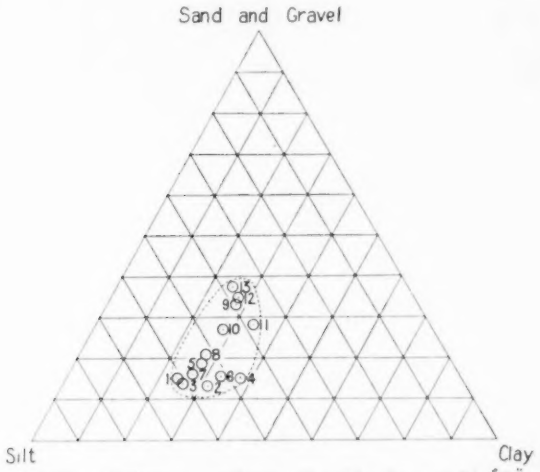


Figure 5. Mechanical analyses of samples from profile "C"

Interpretation of mechanical analysis results.—The size break at 4.5 feet in profile "A" and at 6.5 feet in profile "B" suggests that either this top zone is foreign to the underlying till or that it is a weathering phenomenon. Under the assumption that weathering would produce a gradual rather than abrupt change in size it is suggested that the upper zone is loess which has been subjected to a long period of weathering. In order to check this hypothesis the mineralogy of the sand size of the upper silt zone and the underlying gumbotil was examined. It was found that the sand from the gumbotil and the upper silt zone is made up mainly of clear, conchoidally fractured quartz and it is reasoned that this coarse quartz has not suffered an appreciable amount of weathering. If the upper silt zone was a weathering product of till, then the amount of quartz in the sand size of the silt zone should be approximately the same as the amount of quartz in the sand size of the underlying gumbotil. The quartz sand was separated from the silt and gumbotil samples, weighed and expressed as percent of the total weight of the sand, gravel, silt, and clay in each sample tested. The results, shown graphically in figure 4, indicate a sharp break in the amount of sand quartz at the point where the silt zone begins. This break is regarded as evidence that the silt zone is not a product of weathering but rather a layer of loess which was deposited on top of the Illinoian till. Profile "C," the only sample taken from eastern Indiana, does not show an upper loess zone.

One of the more interesting results of the mechanical analysis is the gradual reduction in size throughout the till profiles. Kay and Pearce (1920, p. 101) in their early work on gumbotil noted many sections where disintegrated boulders exist in the transition zone between the gumbotil and the base of the leached till. It might be pointed out that disintegrated boulders, particularly those composed of metamorphic rocks, are a common feature in all tills

and quite often occur below the base of the leached zone. In many cases these boulders lie below the frost line and in fresh calcareous tills they occur in a mildly alkaline environment. The problem is, how do these boulders disintegrate? Frederickson (1952) has found evidence that channels exist in and

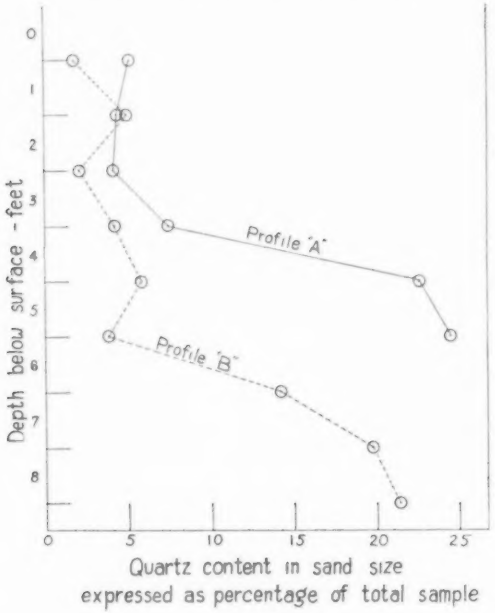


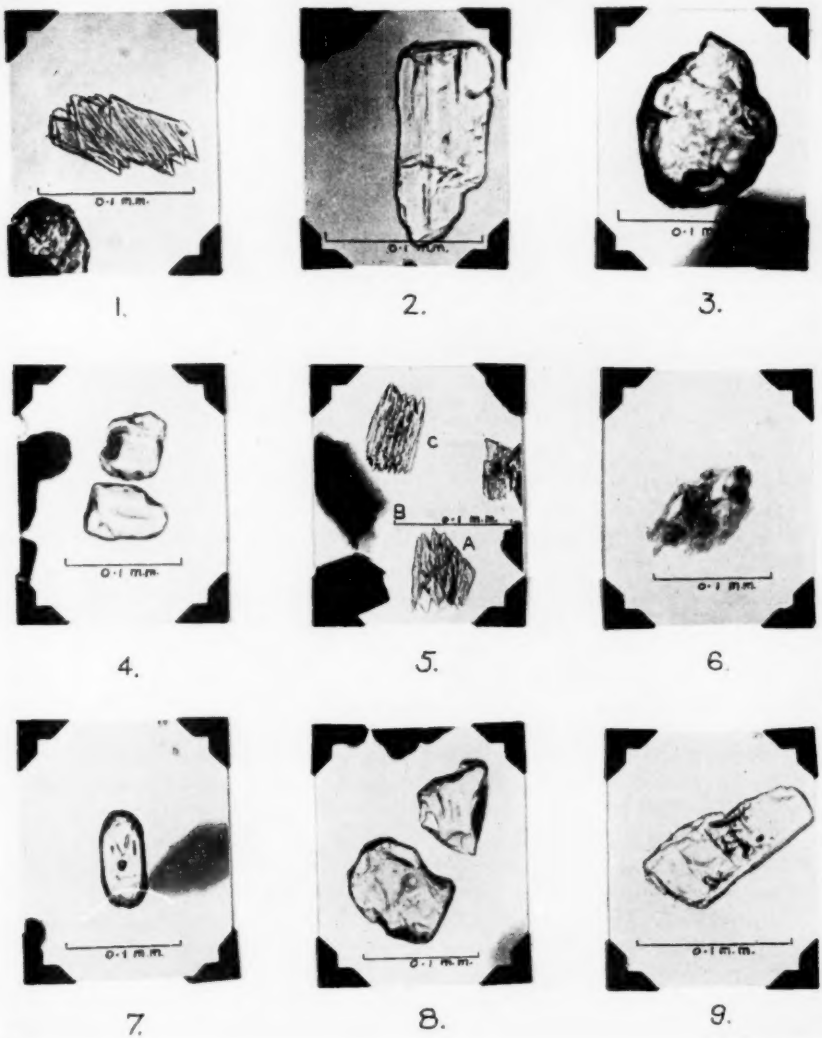
Figure 4.

around the edges of certain minerals in metamorphic rocks. Secondary minerals are sometimes found along these channels which suggests that fluids have migrated along them. In an earlier paper Frederickson (1951) outlines a

PHOTOMICROGRAPHS

1. Hypersthene (from fresh till). Dentate or hacksaw fracture is quite evident in this grain.
2. Sillimanite (from gumbotil).
3. Sphene (from gumbotil). Although this is a relatively clear grain, some of the sphene in the gumbotil has a cloudy appearance.
4. Epidote (from gumbotil). Two grains of yellow epidote which show the freshness of this variety in the gumbotil.
5. Minerals from fresh till.
   A. Augite
   B. Hornblende
   C. Hypersthene
6. Hornblende (from gumbotil). "Motheaten" hornblende showing two holes in the grain which are normal to the cleavage planes.
7. Zircon (from gumbotil).
8. Garnet (from gumbotil). Note fresh conchoidal fracture on these grains from the weathered zone.
9. Kyanite (from gumbotil).

mechanism of weathering whereby water molecules orient themselves on feldspar grains, and the hydrogen ions migrate into the crystal lattice, thus releasing sodium ions. He further suggests that this process will bring about a small volume change at the edge of the crystal due to the repulsion of oxygen atoms once the sodium has left the lattice. In the present case it is believed that ground waters migrating along intergrain channels in the boulders will cause solution at the mineral edges. In time, the overall effect of this solution



will be to loosen the individual crystals and cause disintegration of the boulder. As will be shown later, the presence of amphiboles and other moderately stable minerals in the gumbotil indicates that in this case chemical weathering has not been severe. It is thought that the main factor in the production of the gumbotil is the disintegration of pebbles and boulders into individual mineral fragments which mainly belong to the medium and fine sand sizes. Limited chemical weathering has reduced the sizes of these fragments so that many of them now appear in the silt fraction. The fact that the till sections do not show great changes in the amount of clay suggests that most of the products of weathering are carried away in solution. It should be kept in mind that the presence of the upper loess zone has undoubtedly inhibited the decomposition of the till. Consequently, in areas where this relatively thick loess zone does not exist, Illinoian till will probably show a more advanced stage in the breakdown of silicates.

HEAVY MINERALS

Heavy minerals were separated from each sample of profile "B." It is realized that the degree of weathering might vary in the different sizes of material in the till; however, because of the ease of study, only the heavy minerals separated from the fine sand fraction between 0.147 mm and 0.074 mm were examined. Acetylene tetrabrom-ethane (Sp.G. 2.96) was used to separate the heavy minerals from the light fraction. The heavy minerals were then mounted in aroclor (n 1.66).

Description of Minerals

Opaques.—No attempt was made to give the relative abundance of the metallic oxides and sulphides owing to the difficulty in making a positive identification of these minerals. Table 1 shows that the only significant trend in the amount of opaques throughout the section is the slightly higher percentage in the loess.

Amphiboles.—Green hornblende is by far the most abundant amphibole present. In the lower part of the section, that is, below 12.5 feet, the hornblende has a fresh appearance. Between 12.5 and 9.5 feet there is no appreciable loss in the amount of hornblende, but it displays frayed edges and a motheaten appearance. It is significant to note that weathering does not always progress along cleavage planes but often deep pits appear at right angles to the cleavage. Between 9.5 and 5.5 feet there is a gradual loss of hornblende. In the loess zone the relative amount of hornblende is higher than in the gumbotil, and the hornblende has a slightly fresher appearance.

Brown hornblende appears in small amounts throughout the section and displays weathering effects similar to the green hornblende. A few grains of tremolite were noted below 11.5 feet and none above this depth.

Garnet.—Two varieties of garnet are present: a faint pink to colorless variety, and a red to reddish-brown variety. The pink to colorless garnet is by far the more abundant. Etched grains of garnet were found both in the lower and upper parts of the profile and it is believed that they were etched prior to the deposition of the till. Inasmuch as garnet increases in relative

TABLE 1
Heavy Minerals from Profile "B" (Percentage)

Depth below Surface (feet)	Opaques	Amphiboles	Garnet (pink)	Garnet (red)	Epidote	Pyroxene (Orth.)	Pyroxene (Mon.)	Zircon	Sphene	Staurolite	Tourmaline	Sillimanite	Kyanite	Apatite	Biotite	Rutile	Zoisite
0.5	37.0	19.1	18.6	3.9	6.3	•	1.9	6.4	•	1.6	1.1	1.2	•		•	•	•
1.5	38.1	23.1	17.0	1.7	6.6	•	2.5	5.7	1.0	1.4	•	•	•		•	•	
2.5	36.2	25.4	16.3	4.1	5.9	•	2.4	4.2	1.2	•	•	1.8	•		•	•	
3.5	34.2	25.5	14.3	3.8	7.9	•	3.1	4.5	1.9	1.1	•	1.7	•		•	•	
4.5	31.3	20.5	23.2	4.0	7.3	1.1	3.8	4.0	•	1.9	•	1.6	•			•	
5.5	33.6	16.2	23.0	2.2	11.3	•	1.8	4.3	1.0	2.0	•	1.0	1.3		•	•	
6.5	29.1	19.0	26.8	5.7	8.1	•	2.2	2.3	2.0	2.3	•	•	1.1		•	•	
7.5	29.6	21.8	24.9	5.6	7.0	•	2.1	2.7	3.5	•	•	1.2	•		•	•	
8.5	26.4	28.1	23.6	4.3	7.2	•	3.3	2.1	2.2	1.3	•	•	•		•	•	
9.5	23.9	30.3	21.6	3.8	8.1	•	3.8	1.6	1.6	•	1.0	1.9	•		•	•	
10.5	28.5	29.2	17.1	5.1	7.6	•	3.1	2.8	1.9	1.7	•	•	•		•	•	
11.5	27.5	31.8	13.4	5.3	9.3	1.0	3.6	4.0	2.1	•	•	•	•		•	•	
12.5	33.0	30.5	14.1	3.6	6.1	•	3.9	1.7	2.3	2.1	•	•	•	•	•	•	
13.5	33.3	31.3	12.4	4.0	5.4	1.1	4.6	1.9	1.4	1.5	•	•	•	1.2	•	•	
14.5	32.7	34.2	11.5	3.3	2.2	•	5.9	1.2	1.6	1.2	•	•	•	2.6	1.4	•	
15.5	29.0	35.7	12.5	3.3	3.7	2.3	5.5	1.2	1.7	1.4	•	•	•	1.8	•	•	•

• Less than 1 percent

amount from about 16 percent in the fresh till to about 30 percent in the weathered zone, and for the most part has a fresh appearance, it is considered a stable mineral under the conditions which formed the gumbotil.

Epidote.—Two varieties of epidote are found, one greenish-yellow and moderately pleochroic, the other pale yellow and weakly pleochroic. The greenish-yellow epidote is the more abundant. In general, the amount of epidote increases from about 3 to 4 percent in the fresh till to 11 percent 5.5 feet below the surface. Although there is a greater amount of epidote in the gumbotil than in the fresh till, there are signs of weathering on the greenish-yellow variety in the gumbotil. This weathering appears as pitting and discoloration on the surface of the grains.

Orthorhombic pyroxenes.—Hypersthene is present in small amounts in all samples. Most grains are strongly pleochroic from a bright green to a deep pink. Effects of weathering on hypersthene are evident in the sample 13.5 feet below the surface. Weathering is most severe on the ends of the grains, which gives rise to a dentate or "hacksaw" appearance. This dentate appearance is inherited from the original fracture and is accentuated by weathering.

Monoclinic pyroxenes.—Diopside is the most abundant pyroxene in the till and loess. It is colorless and has a dentate appearance similar to the hypersthene. Diopside shows initial signs of weathering 13.5 feet below the surface. In the gumbotil and loess zones diopside has a surface coating of clayey material which makes identification difficult.

Green, non-pleochroic augite is present in minor amounts in most samples and shows weathering effects similar to the other pyroxenes.

Zircon.—Zircon appears as colorless grains containing numerous inclusions. Both rounded and euhedral forms are found. The loess contains a slightly higher proportion of zircon than the gumbotil. Effects of recent weathering are absent.

Sphene.—Pale brown to colorless sphene is present in small amounts in all samples. In the gumbotil some of the sphene has a cloudy appearance which might be interpreted as incipient weathering. Generally, however, this mineral has a fresh appearance throughout the section.

Staurolite.—Light brown, weakly pleochroic, unweathered staurolite was noted in all samples. Staurolite usually exhibits the typical "Swiss cheese" effect produced by inclusions.

Tourmaline.—Although small amounts of both brown and blue tourmaline are present in all samples, the brown variety is most abundant. No evidence of weathering was noted.

Sillimanite.—Colorless, elongated, unweathered grains of sillimanite are present in all samples.

Kyanite.—Colorless kyanite was found in small amounts in the gumbotil and loess. Kyanite has a fresh appearance throughout the profile.

Apatite.—The lower part of the till contains rounded, clear grains of apatite. Pitted grains were noted in the sample 13.5 feet below the surface, and above 11.5 feet this mineral is absent.

Biotite.—Brown unweathered biotite is present in small amounts in most samples.

Rutile.—Weakly pleochroic reddish-brown rutile is present as a rare constituent. No evidence of weathering was noted.

Zoisite.—Colorless zoisite appears only in two samples. Although no effects of weathering were noted, the scarcity of this mineral makes any statement on its stability unwarranted.

Stability of heavy minerals.—It has been noted by several geologists (Gravenor, 1951, p. 66; Kruger, 1937; Krumbein, 1933) that the types and relative amounts of heavy minerals found within a single till are quite uniform. Most of the heavy minerals in fresh till appear as unweathered fragments and were probably derived from the Canadian Shield. The abundance of heavy mineral types, the uniformity in the relative amounts present, and their fresh appearance in unweathered till makes them ideally suited for a weathering study. Table 2 indicates the relative stability of the heavy minerals found in profile "B."

TABLE 2

Heavy Mineral Stability in Illinoian Gumbotil

Stable	*Moderately stable*	*Unstable*
Zircon	Sphene ?	Apatite
Rutile	Epidote ?	
Tourmaline	Hornblende	
Kyanite	Augite	
Garnet	Diopside	
Biotite	Hypersthene	
Sillimanite		
Staurolite		

Published stability and persistence tables demonstrate that there is a lack of agreement on the position of many minerals within these tables. Apatite, for example, has been reported by Twenhofel (1939, p. 266) and Allen (1948, p. 39) as unstable, whereas Pettijohn (1948, p. 490) believes it to be a stable mineral. Smithson (1941, p. 103) has found uncorroded apatite in residues where garnet is highly corroded, but he states that where corroded apatite is found it is probably the result of recent weathering. Milner (1929, p. 439) believes that apatite survives in impervious rather than pervious rocks and is destroyed by the solvent action of carbonic acid. The instability of apatite found in the Illinoian gumbotil appears to verify Milner's belief that apatite is an unstable mineral under conditions of acid weathering in a porous medium.

Garnet and staurolite are reported by Dryden and Dryden (1946) to be less stable than hornblende, yet in the Illinoian gumbotil garnet and staurolite are clearly more stable than hornblende. Many other minerals which have an uncertain position in the stability series might be mentioned; however, they would only serve to demonstrate that the conditions of weathering, particularly the nature of the soil or intrastratal solutions and the permeability of the material, are of prime importance in determining the stability of minerals. Another consideration is the size of material studied. Quartz, which is normally considered more stable than muscovite in coarse fragments (Goldich, 1938), is found to be less stable than muscovite in clay-size particles (Jack-

son et al., 1948), indicating that the solubility of quartz is probably a linear function of specific surface.

Age of the loess.—The relatively fresh appearance and increase in amount of amphiboles and pyroxenes in the loess suggests that there was a period of weathering of the till prior to the deposition of the loess. The mechanical analyses show that the loess reaches a depth of 6.5 feet in profile "B"; yet at 5.5 feet the amount and freshness of the amphiboles and pyroxenes is less than at 6.5 feet. This anomaly is possibly due to mixing of the loess and gumbotil at the contact zone.

The fact that the loess is thoroughly leached and shows weathering of the moderately stable silicates suggests that the loess is Sangamon in age. However there is no definite proof that it is not as young as Peorian.

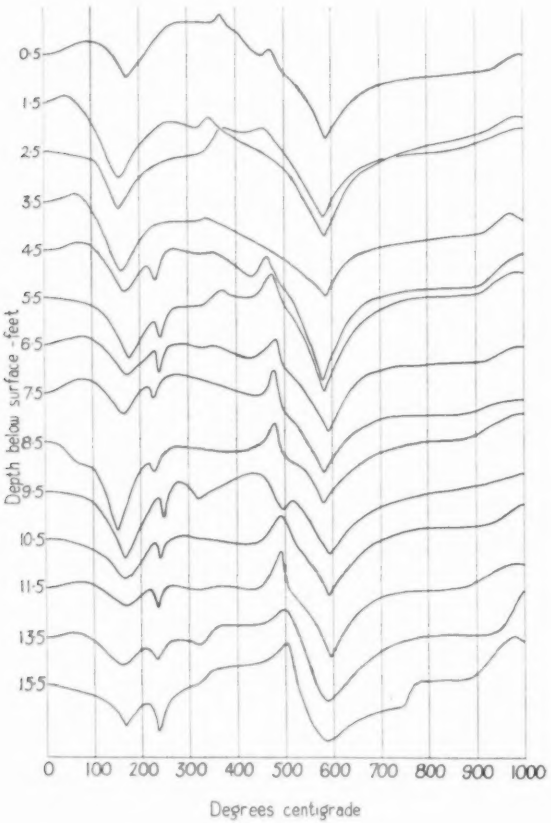


Figure 5. Thermal curves of clay fraction from profile "B"

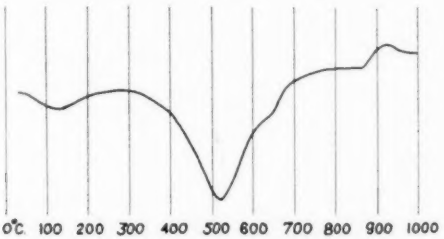
CLAY MINERALOGY

The fine clay fraction, less than 1.0 micron, was removed from each sample of profile "B." These clay samples were tested by X-ray and differential thermal analysis.

Differential thermal analysis.—The thermal curves (fig. 5) were compared with published curves of clay minerals, and it was found that they best fit those given for illite. In the till zone the loss of adsorbed water is marked by a pair of low temperature endothermic peaks. This doublet is absent from the upper part of the loess zone. Montmorillonite frequently shows a low temperature doublet, which has been interpreted by Kerr, Kulp, and Hamilton (1949, p. 25-34) to mean that calcium is the dominant interlayer ion. Grim (1947) has shown that prepared mixtures of illite and kaolinite as well as mixtures of calcium montmorillonite and kaolinite also show this doublet. Grim further notes that this phenomenon occurs in natural clays but that no suitable explanation has been found.

Except for the adsorbed water peaks, the curves obtained from the clay in the loess agree fairly well with an illite curve from the Minford silt of Ohio (from fig. 6, Grim, 1947). The absence of an endothermic peak between 600° and 700° C. and a strong exothermic peak between 900° and 1000° C. suggests that montmorillonite and kaolinite are either absent or that they are present in amounts too small to be recorded by differential thermal analysis.

Perhaps the most important fact shown by these analyses is that there is no major change in the clay mineralogy throughout the profile.



Thermal curve of Minford silt, Ohio - Grim, 1947

fig. 6.

X-ray analysis.—X-ray diffraction spectrometer analysis of each clay sample of profile "B" shows that four minerals, illite, kaolinite, montmorillonite, and quartz are present. As vermiculitic and chloritic minerals have certain reflections similar to those of montmorillonite, the presence of montmorillonite was substantiated by means of ethylene glycol and heat treatments as described by MacEwen (1951, p. 115-116). After the montmorillonite was moistened in glycol it expanded to give a (001) reflection of 17.1A. Another portion of the same clay was then oven-heated, which collapsed the montmorillonite, and it then gave a basal reflection which nearly coincided with the most prominent illite reflection of 10.1A.

The relative intensities obtained from the X-ray spectrometer readings on the clays from the lower part of the till section show that illite is most abundant, kaolinite second, and montmorillonite third. In the upper part of the gumbotil and loess zones there is a small increase in the kaolinite and montmorillonite content. It is estimated from X-ray spectrometer readings and thermal curves that an average clay sample in the section contains 4 to 8 percent montmorillonite, 12 to 18 percent kaolinite, and the rest illite (omitting quartz).

Source and stability of clays.—From the results of the thermal and X-ray analyses it is evident that the clays in the gumbotil have been largely inherited from the fresh underlying till and that illite is relatively stable under the conditions which formed the gumbotil. The similarity of the clay and heavy minerals in the loess zone to those of the till suggests that the source of the loess was glacial material, probably outwash of Illinoian age. The slight increase of montmorillonite and kaolinite in the upper zones of both the loess and till might be attributed either to limited weathering of illite or to small additions of montmorillonite and kaolinite derived from the weathering of moderately stable silicates.

As the clay fraction of the till has been mainly derived from the underlying Paleozoic sediments, the abundance of illite in the till indicates that the argillaceous portion of these sediments is composed chiefly of illite. These results compare favorably with those given by Van Houten (1953, p. 62) and Grim (1942) who report that illite is the predominant clay mineral in most glacial deposits studied to date.

SUMMARY

1. Size analyses of two Illinoian till profiles in western Indiana suggest the presence of a layer of loess on top of the gumbotil. The fact that this loess is leached and displays weathering of the moderately stable silicates suggests that it is Sangamon in age.

2. It is believed that the physical condition of the gumbotil is mainly due to a reduction in size of the coarser fragments in the till. This reduction in size is probably brought about by intergrain solution which causes disintegration of the boulders into individual mineral grains.

3. An examination of the heavy minerals reveals that apatite is unstable, and amphiboles, pyroxenes, and possibly sphene and epidote are moderately stable. Garnet, zircon, sillimanite, tourmaline, staurolite, kyanite, biotite, and rutile appear as stable minerals.

4. The clay-size fraction consists mainly of illite, kaolinite, montmorillonite, and quartz. Illite is the most abundant of the clay size minerals in both the fresh and the weathered till.

ACKNOWLEDGMENTS

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A TEST OF THE REVISED DETERMINATIVE CHART FOR PLAGIOCLASE

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ABSTRACT. New data on the composition and refractive indices of selected plagioclases, recently published by R. C. Emmons and co-workers, are used to test a determinative table presented by the author in 1952. The table seems to be adequate for practical petrographic work, but the possibility that it or the new data contain small systematic biases cannot be excluded. What evidence there is suggests that the bias is located in the new data. .

INTERNAL CONSISTENCY AND PRELIMINARY CHEMICAL CHECK

Appearance of the long-anticipated Geological Society of America Memoir 52 (Emmons, et al., 1953) makes possible the first major test of revised determinative curves for plagioclase based on refractive indices (published in this Journal, Chayes, 1952). The Wisconsin group published refractive index determinations for 30 specimens, of which 25 are accompanied by chemical analyses made by Lee Peck. Analyses of the remaining 5 are by R. E. Stevens. Both men are analysts of excellent and well-deserved reputation. The analyses are undoubtedly of superior quality, and the same may be said of the optical determinations by Messrs. Crump, Ketner and Reynolds.

In table 1, below, are posted:

1. sample numbers and anorthite contents (An_c) from table 5, p. 24, Mem. 52.

2. An values obtained by entering table 5 of Chayes (1952) with the average value for each index, calculated from table 5, p. 24, Mem. 52. (Averages based on direct measurements only.)

Statistical analysis of the table is complicated by the fact that for 26 of the specimens all three indices are given while for 4 only α and γ have been measured directly. Table 2 gives the analysis of variance for An indicated by the index measurements of the 26 specimens in which all three indices have been measured.

The error attached to an individual index determination, as a standard deviation, is thus estimated as $\sqrt{2.03}$ or 1.42 percent An. Index measurements, provided they are made by Messrs. Crump, Ketner and Reynolds, offer what is surely one of the most precise methods for identifying plagioclase.

The conclusion that the specimens do differ in anorthite content hardly requires the support of a variance analysis; it is only the last two lines of the table which concern us. The mean square for indices is not significantly larger than that for error. This is an excellent indication that the determinative chart is at least internally consistent. Examination of the paired differences ($An_\alpha - An_\beta$, $An_\beta - An_\gamma$, $An_\alpha - An_\gamma$) suggests that there may be some slight bias as between An estimates based on α and γ, but the bias, if real at all, fails to attain significance in a sample of this size. In all further calculations, therefore, the *average* value for the optical estimate of An, designated as $An_{\bar{n}}$, will be used. Comparison of An estimates based on indices with those obtained from the chemical analyses is a rather complicated business, involving ana-

TABLE 1

Estimates of An Content Based on Chemical Analysis (col. 2) and Indices of Refraction (cols. 3, 4, 5, and 6)

Specimen No.	An_c	An_α	An_β	An_γ	An_δ
1	0.15	0.9	−0.8	2.9	1.0
2	11.4	13.5	12.6	14.0	13.4
3	16.1	18.9	16.7	17.5	17.7
4	16.6	18.5	18.7	17.0	18.0
5	19.5	19.1	16.5	18.4	18.0
6	35.9	33.1	30.8	33.9	32.6
7	36.1	35.6	37.4	32.7	35.2
8	38.0	35.4	34.2	34.8	34.8
9	49.0	45.7	45.7	43.3	44.8
10	51.6	47.6	46.5	45.5	46.5
11	52.2	50.0	47.8	49.8	49.2
12	56.5	53.9	51.9	52.9	52.8
13	56.2	53.5	50.9	51.8	52.0
14	59.7	54.3	52.2	53.6	53.3
15	60.0	67.7	69.0	60.4	65.6
17	64.5	60.7	62.2	62.7	61.8
19	70.2	68.0	69.4	68.4	68.5
20	70.3	67.5	65.8	66.6	66.3
21	70.3	70.0	68.5	67.9	68.7
22	70.7	68.0	68.6	68.0	68.1
23	73.8	70.0	71.3	69.6	70.2
24	76.8	73.8	73.0	73.6	73.4
25	77.2	73.1	74.4	73.6	73.6
26	78.4	75.3	76.7	77.0	76.2
27	81.5	77.8	79.3	76.4	77.8
28	31.1	27.3	28.0	26.7	27.3
29	0.25	−3.0	—	−2.1	−2.6
30	0.40	−2.4	—	−1.7	−2.0
31	0.40	−2.2	—	−2.6	−2.4
32	20.4	18.0	—	16.4	17.2

lytical accuracy and precision, uncertainties arising from the varying purity of the concentrates and from the method of calculating An_c from bulk analysis.

For a first approximation we may simply ignore all these difficulties and compare the chemical estimate of An given by the authors with An_δ. The comparison may be made from table 1, but is shown for convenience in figure 1. If the chemical and optical procedures were actually estimating the same parameter, the slope of the line of best fit would not differ significantly from unity, and its intercept would not differ significantly from zero (see Youden, 1951, chap. 5). A slope other than unity indicates that there is not a one-to-one relation between increments in the two variables. An intercept other than zero indicates the presence of systematic bias. The equation of the lines shown in figure 1 is:

$$An_c = 1.023\ An_\delta + 1.23$$

Now an intercept of 1.23 is obviously quite different from zero, but the error attached to this estimate is 0.831 and the quotient $t = 1.23/0.831 = 1.48$ fails of significance. The error of the slope is 0.1665, and $t = (1.023 - 1)/0.1665 = 0.138$, for the departure from unit slope, again fails of significance. If the purpose of the examination were merely to determine whether the properties of the new specimens were consistent with a chart known to be correct

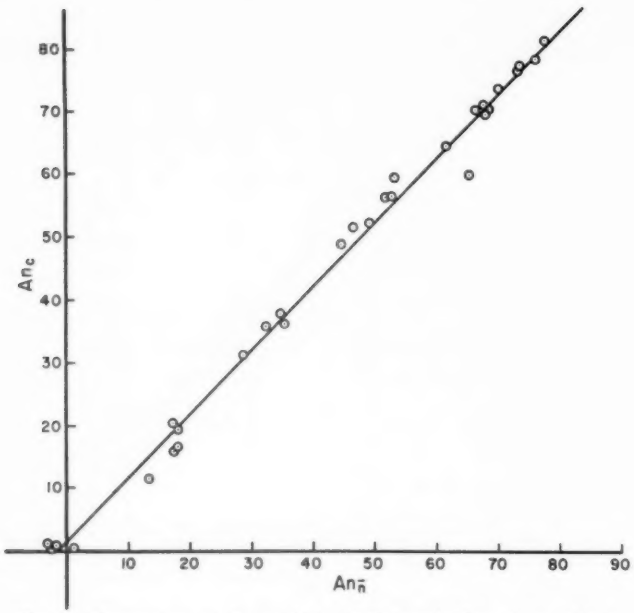

Fig. 1 Comparison of $An_{\hat{n}}$ with An_c, full sample. Data from table 1.

this would end the discussion. Indeed, for most petrographic purposes nothing more *is* necessary.

We do not know that the chart is correct, however, and the attitude of Emmons and his co-workers (see, for instance, p. 23 and 29 of the Memoir) suggests that a chart of this kind would necessarily be crude and inadequate unless chemical analyses could be made on the very *grains* used for the optical work. Closer examination of table 1 suggests that things are not quite as they ought to be if the parent regression does in fact have unit slope and zero intercept, for in 25 of the 30 specimens $An_{\hat{n}} < An_c$. On the assumption that over- and underestimates are equally likely the probability of this or a more uneven partition is .0003. There is clearly some small bias tending to make $An_{\hat{n}} < An_c$, though our estimate of its size fails of significance. The magnitude of the differences plays no part in the calculation of this probability but enters directly in the t-test applied to the intercept, and this is the crux of the matter.

DIFFERENCE ANALYSIS

Every difference $(An_{\hat{n}} - An_c)$ contains a constant contribution from the true difference—which may be zero—and a variable contribution from experimental error, for if there were no error all the differences would be equal and there would be no problem. The variance of the difference is thus a convenient measure of experimental error, and for the data of table 1 it turns out to be 5.952. The difference between expected and observed An values is

thus subject to a standard deviation of $\sqrt{5.952}$ or 2.44 percent An. Now the average value of this difference is only 2.27 percent; it may of course be tested in the same fashion as the intercept ($t = 2.27/2.44$), and the result again falls short of significance.

We have probably gotten this far without hurting anyone's feelings. Devotees of statistics who believe in the full immersion technique will perhaps be a little impatient with this baptism by sprinkling. Those to whom statistical analysis of mineralogical data is anathema will surely realize that every one of the conclusions so far announced could have been "established" in the usual way by inspection of table 1 and figure 1. Most of those who are simply interested in plagioclase, with or without statistics, will probably agree that the consistency of estimates of An based on the different indices is utterly incredible unless the determinative chart is essentially sound and the Wisconsin measurements are in general excellent. Finally, two attempts to establish a difference between optical and chemical estimates of An have failed.

At this point, however, the fur must begin to fly. The two sources contributing to the error variance are perfectly obvious, and, so far as we can tell, quite independent. Knowing the total error variance and the amount contributed to it from one source, we may easily estimate the contribution of the other. Specifically, we have found that the variance of the difference is 5.952; from table 2 the error variance attaching to a single index measurement is seen to be 2.03. Each An_n value is the mean of two or three measurements, so that the error variance attaching to it is 2.03/2 or 2.03/3. Accepting the less favorable value, $5.952 - 2.03/2 = 4.937$ may be taken as an estimate of the variance contributed to the difference by errors and uncertainties involved in sample purification, chemical analysis and calculation of An from the bulk analysis. Thus *more than 80 percent of the variance of the difference is associated with the processes giving rise to the An_c values* and less than 20 percent with the indices and determinative chart.

Now, in view of the excellent fit of the line we surely would not question the intercept of the regression equation unless we had reason to suppose that the line *ought* to pass through the origin. We have reason for thinking—or at least hoping—that this is so. Considering the importance of the conclusion, however, and our predisposition to accept it, we ought to demand more than

TABLE 2

Variance Analysis for An_n of Emmons Specimens in Which All Three Indices Have Been Measured

Source of Variation	Sum of Squares	d.f.	Mean Square
Specimens	38,422.20	25	1536.89**
Indices	7.93	2	3.96
Error	101.39	50	2.03

usual assurance. And in fact we do not have such assurance. The estimated intercept fails of significance, but the probability of t as large as 1.48 is only about 0.15, and the very uneven partition of the signs of the differences ($An_n - An_c$) is certainly cause for suspicion. We cannot have our cake and

eat it too; while it is not quite impossible for the parent variation to be linear with unit slope and zero intercept and still yield a great preponderance of pairs in which $An_c > An_{\bar{n}}$, the probability of such an event is certainly remote. We may suspect that error of the second kind is involved in the tests of intercept or slope; either the slope differs from unity or the intercept differs from zero, or both, and we have failed to detect the true state of affairs.

An unequivocal resolution of the problem requires either better control over experimental error, or less experimental error. If, for instance, the sample preparation and analytical steps had involved even the same rather haphazard replication as the index measurements, examination of the results would be on a much firmer basis. And if a systematic and symmetrical pattern had been followed throughout, the whole discussion would be on a different

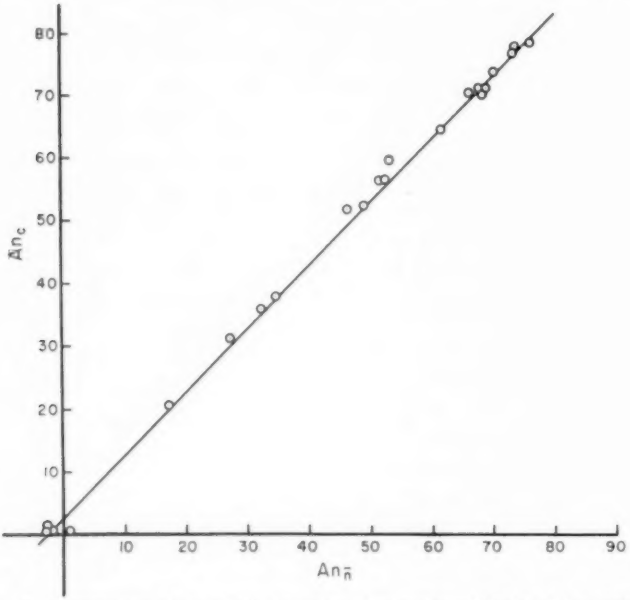

Fig. 2 Comparison of $An_{\bar{n}}$ with An_c after elimination of doubtful An_c values. Data from table 1.

level. Unfortunately, replications can not be inserted *ex post facto;* and we shall be obliged to examine the possibility of improving matters by some elimination scheme which is uninfluenced by whatever relation may exist between $An_{\bar{n}}$ and An_c. Meat axe tactics of this sort are always wasteful—in the present case, for instance, we shall finally discard about 25 percent of the information in table 1—but they are sometimes the only remedy for inadequate planning.

We begin by supposing that departures from the theoretical composition of plagioclase are negligible. On this assumption, in a perfect analysis of a

pure specimen we would always find that

$$4.975\ CaO + 8.474\ Na_2O = 100,$$

and observed departures from this relation would be occasioned by inadequate sample preparation, improper analysis, true exceptions to the rule, or some combination of the three. Allowing what seems a reasonable amount of room for the action and interaction of all three factors, we shall accept all specimens in which $| 100 - (4.975\ CaO + 8.474\ Na_2O) | \leqslant 5$, and reject all others. In this way we shall certainly not reject any common plutonic plagioclases which have been adequately concentrated and correctly analyzed, but may retain impure specimens which have been improperly analyzed. This is not a desirable situation, but in any case we can be quite sure that we have not used the size of the difference $(An_{\tilde{n}} - An_c)$ as a criterion of rejection. In fact, neither the determinative chart nor the measured value of the index has anything to do with the decision. Specimens eliminated by this test include numbers 2, 3, 4, 5, 7, 9, 15, and 27. With the rejections out of the way the regression equation becomes:

$$An_c = 1.011\ An_{\tilde{n}} + 2.62.$$

The error of the slope is 0.01578, that of the intercept 0.8246. For the slope we thus have $t = (1.011 - 1)/0.01578 = 0.697$; values greater and less than this are almost equally likely in samples from a normal parent of unit slope. For the intercept, however, $t = 2.62/0.8246 = 3.11$, a value not likely to be exceeded much more than once in 200 samples unless the true value is in fact greater than zero. The unexplained variation remains extraordinarily small—it is actually somewhat decreased—so that 99.5 percent of the total variance of An_c may be explained as a linear function of $An_{\tilde{n}}$. The intercept is thus to be regarded as an estimate of a constant bias operative over the entire composition range, such that in general $An_c - An_{\tilde{n}} = 2.6$.

INTERPRETATION OF THE REJECTS

Rejection seems to be occasioned chiefly by mechanical impurities. This is clearly true for specimens 4 and 5, in which quartz is a major constituent, and may hold for 2 and 3 as well. Specimens 5, 7, 9, 15, and 17 are rather rich in potash; the memoir remarks that all contain "noticeable sericitic mica," and only number 17 survives the elimination. Specimen 27 contains 0.8 percent combined water, a clear indication of mechanical contamination, or gross analytical error.

Finally, and to my mind most important, in the entire suite of 30 specimens, only 5 (numbers 1, 2, 3, 4, 15) exhibit $An_{\tilde{n}} > An_c$, and all of these but number 1 are among the rejects. It hardly seems likely that dissolved Si and K, which are surely the principal suspects, would *raise* the indices of plagioclase. Contamination with discrete fragments or inclusions of quartz, potash feldspar, or mica would thus seem to be responsible for most or all of the rejections. There is no firm evidence that either improper analyses or departures from the theoretical composition account for any of the rejections.

A POSSIBLE EXPLANATION OF THE BIAS

The principal issue raised by calculations made on the reduced sample

is whether the bias is to be attributed to the determinative chart or to the new data, for there seems little reason to doubt its existence. Unfortunately, all we can do is discuss the matter and take sides, for neither the chart nor the Wisconsin work provides the kind of information which would permit a clear decision.

The Wisconsin sample includes only two specimens, Amelia albite and Bakersville oligoclase, which have been studied in great detail by other optical crystallographers. In both cases the differences between the new and old data suggest that the bias is located in the new data rather than in the determinative chart. Table 3 compares the new values with those I have found in the literature.

TABLE 3

Previous Results for Amelia Albite and Bakersville Oligoclase

Author		α	γ
	AMELIA		
Viola (1900)		1.5292	1.5393
Becke (1906)		1.5285	1.5387
Fischer (1925)		1.5286	1.5385
Meen (1933)		1.530	1.540
Glass (1935)		1.529)	1.539)
		1.528)	1.538)
Hytönen (1952)*		1.529	1.539
	Average	1.5289	1.5389
	Value expected from det. chart for An_6 of Mem. 52	1.5285	1.5388
	Average of observed values, Mem. 52	1.5262	1.5368
	BAKERSVILLE		
Offret (1890)		1.5389	1.5469
Tertsch (1903)		1.5388	1.5463
Tsuboi (1923)		1.5403	1.5481
Duparc and Gysin (1926)		1.5365	1.5456
Hytönen (1952)*		1.539	1.547
	Average	1.5387	1.5469
	Value expected from det. chart for An_6 of Mem. 52	1.5385	1.5467
	Average of observed values, Mem. 52	1.5370	1.5449

*See Chayes, 1952, p. 103.

Only one of the 24 literature measurements, the Duparc-Gysin value for α of Bakersville, is lower than the related Wisconsin value, and the others are all considerably higher. The Bakersville data of Duparc and Gysin are from a paper in which two other plagioclase specimens of very different An content are also described. In all three cases the indices seem very low for the reported chemical composition, and one specimen was actually omitted from the determinative chart calculations partly for this reason.

I do not mean to suggest that the old values are preferable simply because they are old, but only that they are not proved wrong by being ignored.

We are entitled to some explanation of why the Wisconsin results should differ so sharply from those obtained by eleven other workers over a period of more than sixty years. Now there may very well be such an explanation, and it may even require us to question or abandon much of the information about plagioclase indices which has come down to us from the great days of optical crystallography. Until the explanation is presented, however, it seems reasonable to consider the Wisconsin values for Amelia and Bakersville suspect.

Rather, it *would* seem reasonable if the consequences were not so drastic. For the internal consistency of the Wisconsin measurements, the extraordinarily high correlation of An_c with $An_{\tilde{n}}$, and the close approach of the slope of the regression line to unity all indicate that the bias affects all the results and is introduced by a constant error in calibration or procedure rather than a random error in individual measurements. But the "optical glass of known index" used as a standard by the Wisconsin laboratory would have to be off by about 0.0012 in order to account for a constant error of 2.5 percent An. This seems almost as incredible as that all previous determinations of Amelia albite and Bakersville oligoclase should have been in error, on the average, by an amount more than half again as large.

CONCLUSION

For most practical purposes the determinative chart appears adequate. There is perhaps a slight tendency for An estimates to differ a little depending on which index is used, with, commonly, $An_\alpha > An_\gamma$. This might be inherent in the chart or it might be because the chart is based largely on polished prism determinations while the new data are obtained exclusively from fragments. In any case, the effect, if real at all, must be very small; it fails of significance in a sample of 30 differences, which is as large a sample as we are likely to have for a long time.

$An_{\tilde{n}}$ obtained by entering the chart with the Wisconsin index measurements usually underestimates An_c calculated directly from the Wisconsin chemical analyses by somewhere between 1 and 4 percent. In the full sample this tendency fails of significance, but when specimens whose analyses sum to less than 95 percent (weight) of plagioclase molecule are eliminated the bias becomes highly significant. What little evidence there is suggests that this bias is inherent in the new data rather than the chart. Only two of the specimens of the Wisconsin sample are well known in the literature; in both cases the Wisconsin measurements are considerably lower than the averages of the literature values.

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THE PRINCIPLES OF EARLY TETRAPOD CLASSIFICATION

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ABSTRACT. Sound classification should be based upon phylogeny, which is reflected in ontogeny. In the embryo the notochord and associated vertebrae appear first, followed shortly by bony structure protecting the brain. Hence diverse vertebral structure indicates primary subdivision of the tetrapods into the pseudocentrous Urodeles and their allies and the primitively embolomerous eutetrapods. Fundamentally different skull patterns of the latter reflect dichotomy into the latitabular Batrachomorpha (labyrinthodonts, ichthyosaurs, and frogs) and angustitabular ancestors of the reptiles. The reptilian stem is further subdivided into Reptiliomorpha (diadectoids and turtles) which retain an otic notch, and Captorhinia, which lose it. The latter in turn give rise to Theromorpha with one, and Sauromorpha with two temporal openings.

A wealth of saurians have lived on Earth since the end of Devonian time, about 1700 genera. In surveying such a multitude of forms we need well-grounded reasons for our choice of principles of classification. These must not be purely formal indices, but really natural qualities. It seems to the author that the best way is to find a classification which is the result of comprehension of the phylogeny. Therefore phylogeny and ontogeny are compared.

In the ontogeny of a vertebrate the nervous tube and its supporting organ, the chorda dorsalis, develop first. Then in every somite the cartilaginous vertebral arches grow. After formation of the nervous tube small cerebral pouches develop at its forward extremity, which soon need protective sheaths. These facts and this succession must form the basis for classification.

According to the foregoing, the derivation of the vertebrae must indicate the very first radiation in vertebrate phylogeny, and hence the fundamental subdivision in classification. According to Gadow (1896), in every vertebral segment there are first developed two pairs of cartilage blocks: the cranial basidorsale and basiventrale and the caudal interdorsale and interventrale. These two pairs of arcualia are the performation of the vertebra; the haemal arch grows out of the basiventrale. In full-grown vertebrates not all of these cartilaginous arches are preserved; a holomere stage is unknown in tetrapods (fig. 1).

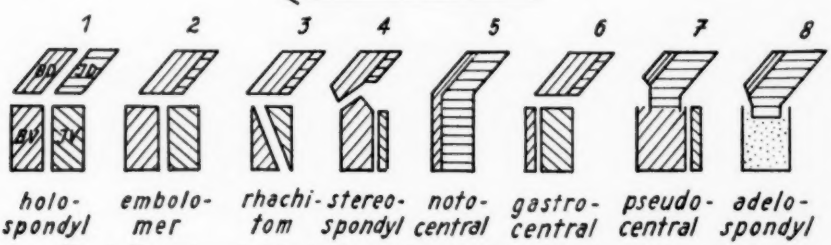

Fig. 1. Formation of eight fundamental types of vertebrae from embryonic arcualia.

In the *embolomerous vertebra* both ventral or chordal elements, basiventrale and interventrale, ossify as the two centra, but only a single dorsal

arch is preserved. The haemal arch in the tail forms part of the anterior centrum.

In the *rhachitomous vertebra* the basiventrale ossifies earlier than the interventrale, leaving but little space for the latter. Hence there are two central elements of different size, the frontal one growing from below, the caudal one growing from above; the haemal arch always forms part of the basiventrale. When the difference in time of ossification increases further, no more space is left for the development of the interventrale, and the *stereospondylous stage* is reached.

If the ventral blocks ossify still later, then from the dorsal part the interdorsale grows down and embraces the chorda dorsalis as is the case in frogs; this is the *notocentral stage*, being derived from the rhachitomous structure. The basidorsale here forms only intervertebral cartilage.

If, however, from the embolomerous stage, not the basiventrale but the interventrale ossifies first, the *gastrocentral vertebra* is formed, leading by a short phylogenetic history from the embolomerous stage to a single full centrum formed by the interventrale, with the basiventrale left as a small intercentrum only. In this case in the tail the haemal arch is a separate ossification, because it originates from the basiventrale.

Quite another mode of development is shown by the *pseudocentral vertebra*. Here the neural arch consists of the interdorsale, and among the chordal arches the basiventrale ossifies quickly, while the slow-growing interventrale becomes only intervertebral cartilage. Therefore also no haemal arch can be formed. Secondarily, another case is possible: the interdorsale ossifies as neural arch and the basiventrale is slow, and before that begins to ossify, the sheath of the chorda begins to calcify and separates inwardly other calcified lamellae, so that a calcareous amphicoelous centrum originates. This is the *adelospondyl vertebra*, described by Watson (1926), a structure comparable to the vertebra of the sharks.

From these features in the formation of vertebral structures we may learn the most fundamental classification.

The most primitive cases and at the same time the most primitive structures which cannot directly be developed out of each other are the pseudocentral and the embolomerous structures. Pseudocentrophori are the Urodela and their Permian predecessors, part of which have the limited specialization of adelospondylous vertebrae. Embolomerous vertebrae are found in the Loxembolomeri and the Anthrembolomeri, beginning in Carboniferous time. These two branches and their early descendants have temnospondylous vertebrae. They are roots of the Eutetrapoda in contrast to the Pseudocentrophori (Urodelomorpha) with primitively holospondylous vertebrae. According to Jarvik the Pseudocentrophori or Urodelomorpha are descendants of the porolepiform Crossopterygia, while all Eutetrapoda according to Säve-Söderbergh and Stensiö are descendants of the osteolepiform Crossopterygia. This is the fundamental branching into two main stems.

According to the ontogenetic scheme, the next most primitive facts will be found in the protecting elements of the cerebrum, that is, in the temporal

part of the skull behind the orbit. This part of the skull can be closed, the most primitive and ancient condition. So it is in the Loxembolomeri and in the Anthrembolomeri. Descendants of the Loxembolomeri are the rhachitomous Stegocephalia, according to Watson (fig. 2), and their later stereospondyl stage, and—as only quite recently shown by Nielsen[1]—the early

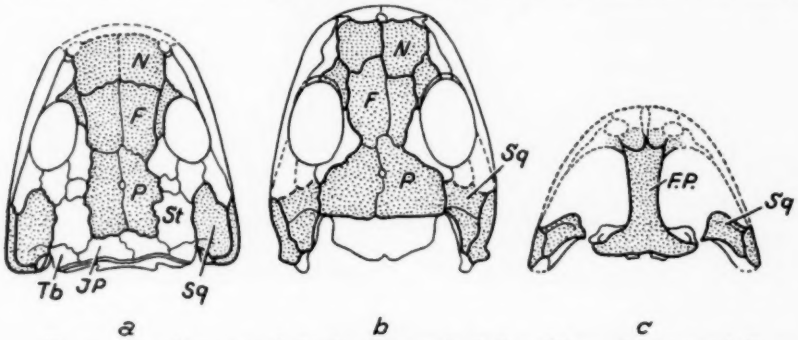

Fig. 2. Transformation of the batrachomorph skull roof from the Stegocephalia to the frogs. a) *Eugyrinus*, b) *Miobatrachus*, c) *Protobatrachus*, after Watson.

embolomerous Ichthyosauria. This whole branch with closed temporal skull roof derived from the Carboniferous Loxembolomeri are the Batrachomorpha up to the present-day frogs.

Though both the Loxembolomeri and the Anthrembolomeri have embolomerous vertebrae, there is a significant difference in the structure of the ossified skull table. In comparison with the primitive crossopterygian skull

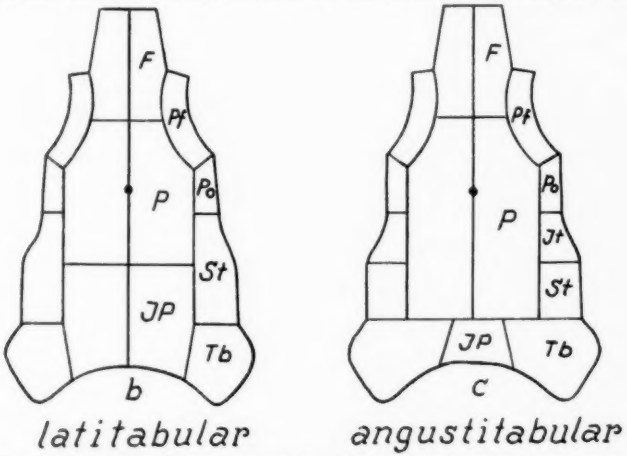

Fig. 3. Arrangement of bones on skull table in Batrachomorpha (latitabular) and Anthrembolomeri (angustitabular). Modified from Säve-Söderbergh.

[1] Dr. Eigil Nielsen of Copenhagen has generously authorized the author (personal communication, July 3, 1952) to publish these facts before his own first paper appears. To my knowledge it has not appeared yet, though I have photographic pictures of his plates.

roof these primitive tetrapods have the parietals and interparietals of different relative size, according to Säve-Söderbergh (1932), as shown in figure 3. In the Batrachomorpha the interparietals are broader than the parietals ("latitabular"), in the Reptiliomorpha they are narrower, so that the tabulars touch the parietals ("angustitabular"). In a single line of the Batrachomorpha (the latitabular first ichthyosaurs) with closed temporal skull roof and a single "metapsid" temporal fenestra arises between postfrontal and supratemporal.

The Diadectoidea as the beginning of the Reptiliomorpha and the Captorhinia both come from the Anthrembolomeri. They all have a stegal (closed) skull roof. But the Captorhinia are further advanced in having lost the otic notch. Already in some of the very last Captorhinia and in their descendants, the early Theromorpha, a single synapsid temporal fenestra is beginning between postorbital and squamosal.

The twin branch of the Theromorpha, the Sauromorpha, beginning with the Permian Eosuchia has two "diapsid" temporal openings, separated by postorbital plus squamosal, and, if the lateral of these fenestrae is not fully framed, as in the Squamata, this would be the "katapsid" stage.

These primitive features concerning the development of vertebral structure and the structure of the skull roof thus give (fig. 4) the four great

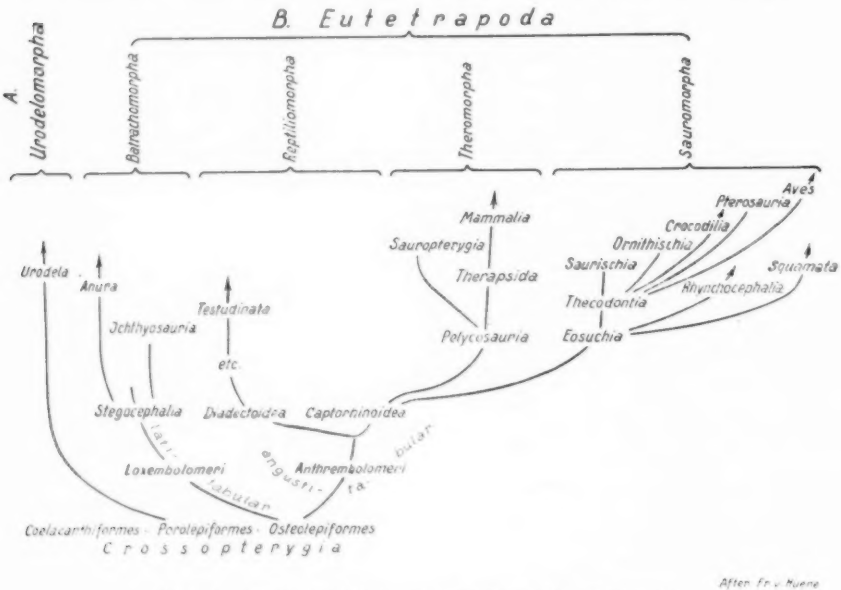

Fig. 4. Principal phylogenetic branches of the Tetrapoda.

dichotomies in early tetrapods: 1) Urodelomorpha and Eutetrapoda, 2) Loxembolomeri and Anthrembolomeri, 3) Reptiliomorpha and Captorhinia[2], 4) Theromorpha and Sauromorpha.

[2] The Captorphinia are Reptilimorpha also, but are a highly specialized branch.

Thus some fundamental features give a simple main classification of the wealth of early Tetrapods. Later sequences are similar on higher bases. By such a mode of searching, classification becomes a picture of phylogeny.

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REVIEWS

Physical Chemistry of Metals; by L. S. DARKEN and R. W. GURRY. P. ix, 535; figs. New York, 1953 (McGraw-Hill Book Company, $8.50).—There would probably be a general agreement among metallurgists that the field of theoretical metallurgy may be separated roughly into topics that fall under the headings of physical chemistry and of physics. The choice of specific topics to be included in each category, however, would be a matter of personal taste and the final choice would of necessity be somewhat arbitrary. The authors of the present volume feel that there exists a fairly distinct newly developed field which may be called "the physical chemistry of the metallic state" and attempt to present the principal topics of this field in their book.

The first section of the book is concerned with the atomistic nature of the crystalline state, as well as the liquid and gaseous states of matter. It is essentially descriptive in nature, covering such topics as atomic radii, lattice imperfections, the Hume-Rothery rules for alloy formation, and the theory of the metallic bond from the point of view of Pauling. The presentation of the Pauling theory, though brief, is welcome since it is not usually covered in textbooks on metals. The alternative, more widely adopted, Brillouin zone theory of metals is barely mentioned on the ground that "it has contributed much to physics but little to chemistry." In general, topics heavily accented in texts on the physics of metals, such as electrical and mechanical properties, are almost completely omitted here in an attempt to draw the line between physics and chemistry of metals as sharply as possible. About 130 pages are devoted to the descriptive part of the book.

By far the largest section (300 pages) is the second, dealing with thermodynamics. A thoroughly classical treatment is given, starting from first principles and differing from standard treatments of chemical thermodynamics only in that the theory is developed primarily as required for metallurgical problems. Thus the study of heterogeneous equilibrium and of temperature-pressure diagrams is emphasized. Illustrative examples include an unusually great emphasis on iron and steel. In addition, special attention is given in two separate chapters to the iron-nitrogen and iron-carbon systems. These chapters transcend the textbook level; they serve as excellent summary articles and contain much thermodynamic data on these two systems. This unusual emphasis on the ferrous side of metallurgy will surely be forgiven when it is recalled that the authors are among the foremost authorities on the thermodynamics of ferrous materials. It is worth noting that the thermodynamic section is independent of the earlier descriptive part of the book.

The final section consists of two chapters. Here it appears that the authors realized that their original purpose of treating all of the physical chemistry of metals in one book was too ambitious. To carry the original plan to completion would involve the subjects of diffusion and reaction kinetics from both the phenomenological and atomistic points of view. The theory of nucleation and growth should be developed and a more detailed study of lattice defects would become necessary. Such a treatment would link both the atomistic viewpoint of the first section and the thermodynamic concepts developed in the second section to form a well-coordinated whole. Probably because a satisfactory presentation of such a third section would

make the book excessively long, the authors chose to compromise by including one chapter on the phenomenological theory of diffusion (to which field Dr. Darken's own research has made a notable contribution) and a final chapter on reaction-rate theory as a "token acknowledgement of the great importance of this rapidly growing field." The subject of nucleation and growth is only briefly mentioned (although previously touched upon in relation to the thermodynamics of solidification) and the atomistic approach is practically omitted. As a result, the three sections of the book are left hanging as more or less separate entities.

It seems to this reviewer, that this book will be principally used for its second section, as a textbook in metallurgical thermodynamics. As such it forms a valuable addition to the literature of metallurgy. An excellent set of problems developed by Professor M. B. Bever of M. I. T. increases the value of this volume as a textbook.

A. S. NOWICK

The Scientific Adventure; by HERBERT DINGLE. P. ix, 372; 5 figs. New York, 1953 (Philosophical Library, $6.00).—The author, who is Professor of History and Philosophy of Science at University College, London, considers highly important the fact that London University awards advanced degrees in the History and Philosophy of Science. He regards as deplorable the lack of scientists devoted to a critical study of the foundations of their own field and applauds any positive indication that some recognition is given to this need. The introductory chapter of this book points out that such recognition is far from universal and presents arguments for the necessity of rectifying the situation.

Each chapter consists of a lecture or an article written by Professor Dingle within the past sixteen years. As usually happens in a book composed of a collection of essays written with no intention of being incorporated into a single volume, some repetition occurs. This is not necessarily undesirable, for often the portions involved deserve the emphasis they receive in the process of repetition. Some readers may be disturbed by statements in the book which they consider to be oversimplifications; most such statements can be attributed to the conciseness required by the space limitations of a relatively short essay rather than to the author's lack of realization of the true complexities involved.

The first half of the book contains a critical interpretation of the history of science and is concerned largely with astronomy and astronomers. In the remainder of the articles the author attempts to explain, justify, and apply the form of scientific philosophy which he advocates. Two philosophical viewpoints on the nature of science are discussed. One view regards science as attempting to organize the primary sense-data of experience into a rational system, while the other asserts that science is concerned with learning as much as possible about a "pre-established, independently existing world of mind and matter." Professor Dingle contends that the former affords a more advantageous perspective with which to interpret modern physics than does the widely held second viewpoint. He illustrates the applicability of his phil-

osophical viewpoint to a wide range of fields, including religion and the humanities. Dingle states in the preface that "the unity of the book is to be found in its viewpoint, and such value as it may have arises from the degree to which it succeeds in making the advantages of that viewpoint clear."

This clearly and cogently written book deserves a respected position among the rapidly growing literature on the philosophy of science.

A. A. EVETT

The Composition and Assaying of Minerals; by JOHN STEWART-REMINGTON and WILFRED FRANCIS. P. viii, 127. New York, 1953 (Philosophical Library, $5.50).—According to the preface, "the book relates primarily to the chemical composition of minerals, with the object of providing a handy guide to their qualitive and quantitative examination that is suitable for use by mineralogists, metallurgists, geologists, chemists in mine laboratories, and students in schools, technical colleges, and universities." Most of the book, pages 10 to 91, considers the elements Ag, Pb, Hg, Bi, Cu, Cd, As, Sb, Au, Pt, Fe, Al, Cr, Ti, Mo, W, Zn, Mn, Ni, Co, U, V, Ba, Sr, Ca, Mg, K, and Na, with brief statements of the properties of the principal minerals in which the elements are found, qualitative tests, and methods of quantitative analyses.

The reviewer questions whether the objectives set forth could possibly be met in the space allotted. The sections on qualitative tests and quantitative assays are necessarily sketchy with little discussion of possible interferences; the sections on occurrence and mineralogy are marked by poor choice of occurrences, archaic nomenclature, and many erroneous statements of the composition of minerals. The price of the book seems much too high.

MICHAEL FLEISCHER

Imperfections in Nearly Perfect Crystals, a Symposium held at Pocono Manor, October 12-14, 1950; editors, W. SHOCKLEY, J. H. HOLLOMAN, R. MAURER, and F. SEITZ. Sponsored by the Committee on Solids of the N. R. C. Division of Physical Sciences. P. xii, 490. New York, 1952 (John Wiley & Sons, $7.50).—The mere names of a score of prominent authors make this a notable symposium. Their treatments of important subjects justify expectations. Seventeen different papers are included in four major sections. Part I, "On the Nature of Imperfections in Nearly Perfect Crystals," is concerned with basic theoretical concepts. Frederick Seitz' thorough synthesis includes a systematic list of the kinds of imperfections considered, and indicates their interrelationships. M. T. Read and W. Shockley explain and theorize the geometry of dislocations. Part II, "The Role of Imperfections in Deformation," is written by and for metallurgists and physicists, but it should be widely read by geologists interested in the mechanisms of deformation of rocks and minerals. As pointed out in the preface to the book, there is a considerable gap between the first two parts: the one purely theoretical, the other more experimental and less theoretical; the one devoted to presumed phenomena on an atomic scale, the other to those more directly observable. Yet this very gap shows where new studies and new techniques are needed. Part III, "Dif-

fusion and Related Phenomena," will excite the petrologist and the mineralogist; it should offer the enthusiastic petrologist transformist much food for thought and discussion, as will also Part IV, "On the Properties and Effects of External and Internal Surfaces of Crystals." Particularly Smoluchowski's data (chapter 17) on movement and diffusion in grain boundaries should have the attention of geologists: here are quantitative data over which the students of the origin of granite may argue and argue; here, also, are methods by which mineralogists might well determine actual diffusion rates in geologically important aggregates. The evidence for vectorial variations in diffusion rates, dependent upon the crystallographic orientation of the two grains adjacent to a given boundary, would encourage one to expect very important variations in foliated rocks. We believe this book will open new fields of research to many geologists.

HORACE WINCHELL

Geology and Ground Water Resources of the Baltimore Area; by R. R. BENNETT and R. R. MEYER. Maryland Department of Geology, Mines and Water Resources Bulletin 4. P. 573; 30 figs., 26 pls. Baltimore, 1952 (Johns-Hopkins University, $7.50, cloth bound; $6.00, paper bound).—Except for use of the public water supply, the Baltimore industrial area is dependent upon ground water. Concentration of the industry adjacent to the Patapsco River has led to overpumping, lowering of water levels, and salt contamination of the ground water.

This publication is a comprehensive investigation of the ground-water resources and geologic formations of this area. It has been prepared with extreme care and presents a complete description of these resources with recommendations regarding their future use and development.

There are two principal water-bearing formations in the area. Both of them have been extensively pumped and utilized by industries. Wells in the Patuxent formation yield 200 to 300 gallons per minute near its outcrop; other wells, located at depth in the stratum, yield 500 to 900 gallons per minute. The Patapsco formation is divided by a clay bed into two aquifers. Where the full thickness of the formation is present, wells in these aquifers yield 500 to 800 gallons per minute.

Ground-water pumpage in the industrial districts reached a peak of 32,700 gallons per minute early in 1942, after which it was reduced to 24,285 gallons per minute. In 1945, the artesian head was from 40 to 100 feet below the land surface in the Patuxent formation and from 10 to 50 feet in the Patapsco formation. Detailed chemical analysis of many samples disclosed that the wells were contaminated by infiltration of salt water from the Patapsco River, an estuary of the Chesapeake Bay, and also by industrial wastes, primarily sulfuric acid. The Patuxent formation has been contaminated also by leakage of highly mineralized water through defective wells.

The aquifers are recharged from precipitation on their outcrops, and the potential rate of recharge exceeds the theoretical maximum quantity of water that can be transmitted through them. However, the concentration of

pumping in some parts of the area is sufficiently great to prohibit the development of additional ground-water supplies. In several localities the "safe yield" has been exceeded.

The ground water is especially suited for industrial use because of the relatively low cost of pumping, uniform temperature (making possible utilization for cooling), and normal low mineral content. It is apparent from the volume of water pumped that to abandon these sources for industrial use would be an economic loss of considerable magnitude.

Many charts, tables, maps and detailed data are included in the report, making it a valuable source of reference material. Their compilation was a huge task and indicates the magnitude of the survey. Use of these data will be an important factor in the future economic development of this area by industrial water consumers.

This investigation was a cooperative project by the United States Geological Survey, the Maryland Department of Geology, Mines and Water Resources, and the Bureau of Water Supply of the City of Baltimore.

EDWARD S. HOPKINS

Understanding Iowa Soils: An Introduction to the Formation, Distribution, and Classification of Iowa Soils; by ROY W. SIMONSON, F. F. RIECKEN, and GUY D. SMITH. P. vi, 142; 48 figs. Dubuque, Iowa, 1952 (Wm. C. Brown Company, $3.00).—This book describes the soils as they occur in Iowa. Before discussing the soils in detail, the authors describe what is meant by a soil profile. This includes the characteristics found in A, B, and C horizons and how these horizons may be told apart. They also go into some of the fundamentals or factors of soil formation such as climate, living organisms, topography, time, and soil parent material. Since the kind of soil parent material occurring in Iowa is dependent to a large extent on the glacial geology of the state, the authors briefly discuss this.

A very brief discussion is given of the classification of soils before taking up the great soil groups as they occur in Iowa. These great soil groups are Brunizems, Gray-Brown Podzolic, Planosols, Humic-Grey soils, Alluvial soils, Lithosols and Bog soils. Characteristics of the groups are illustrated with typical profiles and landscapes.

The remainder of the book describes the characteristics of the 20 soil associations found in the state. The names of some of these associations are well known such as the Clarion-Webster, Tama-Muscatine, Marshall, Shelby-Grundy-Haig, Fayette and Clinton-Lindley. New soil names occur as a result of intensive field studies as well as laboratory work. For example, the Marshall series formerly covered a much larger area than is now shown. Textural differences, degree of acidity, and topographic position have narrowed the range of this series and added others.

The book is well illustrated with photographs showing major profiles, landscapes and kinds of crops grown. A unique feature is the block diagrams of soil patterns as they are related to parent materials, topography and vegetation in the various associations. These diagrams are instructive in pointing

out clearly the differences obtained in soils when differences occur in topography, drainage and vegetation.

The physical and chemical properties are given of some of the representative soils. It would have been helpful if some of these tabular data had been graphed for easy reference and understanding. The bibliography contains references on soils in general and soils of Iowa in particular. A glossary gives information on terms which may not be understood by people not trained as soil scientists. The text is easy reading.

This book should be especially useful to people in Iowa interested in soils and also of interest to soil scientists, agronomists, geologists, engineers and others interested in soil. It would be desirable if publications on the soils of other states similar to this could be published.

C. LOYAL W. SWANSON

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